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NASA General Working Paper No. 10 046

AN ANALYSIS OF A CHARRING ABLATION THERMAL PROTECTION SYSTEM

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

June 4, 1965

N70-35756

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AN ANALYSIS OF A CHARRING ABLATION THERMAL PROTECTION SYSTEM

By Donald M. Curry

SUMMARY

An analytical model is presented for predicting the transient one-dimensional thermal performance of a charring ablator heat protection system when exposed to a hyperthermal environment. The heat protection system is considered to consist of an ablation material and backup structure. The ablating material is further considered to consist of three distinct regions or zones; char, reacting, and virgin material.

A Fortran IV digital computer program (STAB II) utilizing an implicit finite difference formulation has been written for the IBM 7094/40 computer system. The program considers one ablating material and a maximum of 12 backup materials with conduction or radiation and/or convection allowed between materials. Thermal properties of all materials are temperature dependent with the properties of the charring material also state dependent.

The governing differential equations and their implicit finite difference formulation are presented. The program input and output is described in detail. Also, a comparison of theoretical and experimental results is shown.

INTRODUCTION

The analysis and design of thermal protection systems for entry into an atmospheric environment has resulted in a voluminous amount of literature on the general subject of ablation. (See refs. 1 and 2 for a survey of information on ablation.) The ablation materials may generally be classified into three categories; subliming, melting and vaporizing, and charring. The charring ablator normally provides the most efficient thermal protection shield for the major portion of a manned entry vehicle. This report describes a method for predicting the thermal response of a typical charring ablation material. The response of a charring material to a hyperthermal environment is extremely complex and the mathematical model presented to analyze the transient behavior of the material contains simplifying assumptions and approximations necessary to afford even a numerical solution.

The equations derived in this analysis have been programed in Fortran IV for an IBM 7094/40 computer system. The numerical formulation of this digital program, designated STAB II, is such that an implicit solution is obtained. The input, output, and various program options are discussed in detail.

The thermal response of a typical charring material as predicted by STAB II is compared with arc tunnel test results. As shown, the predicted in-depth temperatures are in excellent agreement with the measured values.

The author wishes to express his appreciation to Barbara D. Arabian, Bette J. Stafford, and Davis D. Bland for their assistance in the preparation of the digital computer program.

SYMBOLS

C_p	specific heat
F	exterior view factor
F_{env}	view factor-emissivity product to cabin environment
H_d	heat of virgin material degradation
H_T	total enthalpy
H_w	wall enthalpy
H_{300}	enthalpy of air at 300° K
h	film coefficient between backup materials
h_{env}	film coefficient between last backup material and cabin environment
k	thermal conductivity
$\dot{m}_c$	mass loss rate of char material

$\dot{m}_g$	gas ablation rate
NP	number of nodes in ablation material
$\dot{q}_{c\ Blow}$	hot wall convective heat flux with blowing
$\dot{q}_{comb}$	heat flux due to combustion
$\dot{q}_{cw}$	cold wall convective heat flux without blowing
$\dot{q}_{rad}$	radiation heat flux
S	surface recession depth
$\dot{S}$	surface recession rate
T	temperature of node beginning of time step
T_{env}	cabin environment temperature
T'	temperature of node at end of time step
T_∞	radiation heat sink temperature
VL	thickness of ablation material
ΔH_c	heat of combustion per unit weight of char
ΔX	thickness of a node
$\Delta\theta$	time step $(\theta' - \theta)$
ϵ	emissivity of material
η	transpiration cooling efficiency
θ	initial time
θ'	final time
ρ	density
σ	Stephan-Boltzman constant

Subscripts:

c	charred state
i	node number
j	material number
v	virgin state

PROGRAM DESCRIPTION

The following general requirements were established before writing a digital computer program to analyze a charring ablation system:

a. Stability of the equation for all applications.

b. Machine running time short enough to make use of the program economically feasible (a minimum of turn around time per problem).

c. A minimum of input per problem.

d. A wide variety of boundary conditions for application to both trajectory data and ground or flight test data analysis.

STAB II has been formulated in Fortran IV to analyze the transient thermal performance of a charring ablator heat protection system. The program considers one ablating material and up to 12 different backup materials with or without air gaps. Pure conduction or radiation and/or convection between backup materials is allowed. The ablation material may be divided into a maximum of 50 nodes and each backup material may be subdivided into a maximum of 10 nodes. The thermal properties of the materials are in tabular form and are temperature dependent. The ablation material is also dependent upon its state, that is, fully charred, partially charred, et cetera.

The following surface boundary condition options are provided:

a. Cold wall convective and radiative heat flux tables as a function of time. These components are specified separately, since mass transfer at the surface blocks part of the convective heating, but in general, has no effect on the radiant heating.

b. Surface temperature as a function of time.

c. Surface recession as a function of temperature or time. Surface recession as a function of temperature and pressure is also available.

Heat loss to the interior environment for the last node of the backup structure can be specified by two methods:

a. Conduction into the node and radiation and/or convection loss to the interior environment.

b. Conduction into the node and adiabatic wall.

The STAB II numerical formulation of the equations describing the response of the heat shield is such that an implicit solution has been obtained. It is well known that numerical solutions of partial differential equations are subject to several different types of errors. The first of these is the truncation error, due to the use of a finite subdivision. This error may be reduced by simply choosing a smaller subdivision, ΔX. The exact values are approached more and more closely as ΔX decreases. The second kind of error is the numerical, or roundoff error. The way in which this numerical error grows or decays with time determines the stability of the difference equation.

To illustrate the differences in the explicit and implicit equation form, consider a nonablating homogeneous solid. The one-dimensional Fourier conduction equation, neglecting any heat generation terms, is:

$$\frac{\partial}{\partial X}\left(k\frac{\partial T}{\partial X}\right) = \rho c_p \frac{\partial T}{\partial \theta} \tag{1}$$

The finite difference form of equation (1) written in the conventional forward time step or explicit form for the i^{th} node is

$$\frac{\left(T_{i-1} - T_i\right)}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} - \frac{\left(T_i - T_{i+1}\right)}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} = \rho c_p \frac{\Delta X\left(T_i' - T_i\right)}{\Delta\theta} \tag{2}$$

where the prime superscript denotes values at the end of the time step,

$$\Delta\theta = \theta' - \theta$$

For explicit conduction solutions, the following stability criteria has been established:

$$\frac{\rho c_p}{k} \frac{(\Delta X)^2}{\Delta\theta} \geq 2$$

which places an upper limit on the time step $\Delta\theta$ for a fixed truncation error. This criteria can require a prohibitive amount of machine time.

Liebmann (ref. 3) advocated a solution of the equation which does not require this stability criteria. The finite difference equations are written in a backward time step form which affords an implicit solution.

The implicit (backward time step) difference form of equation (1) for the i^{th} node is:

$$\frac{\left(T'_{i-1} - T'_i\right)}{\dfrac{\Delta X}{2k_{i-1}} + \dfrac{\Delta X}{2k_i}} - \frac{\left(T'_i - T'_{i+1}\right)}{\dfrac{\Delta X}{2k_i} + \dfrac{\Delta X}{2k_{i+1}}} = \rho c_p \frac{\Delta X\left(T'_i - T_i\right)}{\Delta\theta} \tag{3}$$

Equation (3) uses the temperature differences at the end of the finite time interval instead of the beginning, as in the explicit method, equation (2). T_i is the only known temperature in equation (3), but there are corresponding equations for each point in the system and all are solved simultaneously yielding the temperature at each node.

Collecting all unknown temperatures on the left side of the equation and the known temperature on the right side, equation (3) is:

$$\left(\frac{1}{\dfrac{\Delta X}{2k_{i-1}} + \dfrac{\Delta X}{2k_i}}\right)T'_{i-1} - \left(\frac{1}{\dfrac{\Delta X}{2k_{i-1}} + \dfrac{\Delta X}{2k_i}} + \frac{1}{\dfrac{\Delta X}{2k_i} + \dfrac{\Delta X}{2k_{i+1}}}\right.$$

$$\left. + \frac{\rho_i c_{p_i} \Delta X}{\Delta\theta}\right)T'_i + \left(\frac{1}{\dfrac{\Delta X}{2k_i} + \dfrac{\Delta X}{2k_{i+1}}}\right)T'_{i+1} = -\left(\frac{\rho_i c_{p_i} \Delta X}{\Delta\theta}\right)T_i \tag{4}$$

Equation (4) is in the form of:

$$AT'_{i-1} + BT'_i + CT'_{i+1} = D \tag{5}$$

STAB II generates such an equation for each node in the system.

Since radiation is an important mode of heat transfer in charring ablative systems, a problem is encountered in any equation containing a radiation term. The radiation heat flux, written in a backward difference form is:

$$\dot{q}_r = F\epsilon\sigma\left(T_i'^4 - T_\infty^4\right) \tag{6}$$

This term cannot be used in an implicit solution since the unknown temperature T_i' is to the 4th power. The 4th power unknown can be eliminated by the following linearization:

$$\left(T_i'\right)^4 = \left(T_i + \Delta T\right)^4 = T_i^4 \left(1 + \frac{\Delta T}{T_i}\right)^4 \tag{7}$$

where

$$\Delta T = T_i' - T_i$$

let

$$X \equiv \frac{\Delta T}{T_i}$$

and rewrite equation (7)

$$\left(T_i'\right)^4 = \left(T_i\right)^4 (1 + X)^4 \tag{8}$$

If X has an absolute value <u>near zero</u>, the following is true:

$$(1 + X)^4 \cong 1 + 4X \tag{9}$$

Now substituting (9) into (8)

$$\left(T_i\right)^4 \cong \left(T_i\right)^4 (1 + 4X) = \left(T_i\right)^4 \left(1 + 4\,\frac{\Delta T}{T_i}\right) \left(T_i'\right)^4$$

$$\cong 4T_i^3 T_i' - 3T_i^4 \tag{10}$$

Equation (10) is a linearized approximation of equation (7) in which the unknown temperature is only to the first power. The assumption in equation (10) is that $\Delta T/T_i$ has an absolute value near zero. Figure 1 is a plot of the error obtained when $(1 + 4X)$ is substituted for $(1 + X)^4$. For most ablation problems where the surface temperature is high and the radiation losses are significant, the value of $\Delta T/T_i$ can easily be controlled to values of less than ± 0.1.

Therefore, equation (6) can now be written

$$\dot{q}_r = F\epsilon\sigma\left(4T_i^{\,3}T_i' - 3T_i^{\,4} - T_\infty^{\,4}\right) \tag{11}$$

Using the linearized approximation for the radiation terms, the resulting system of implicit difference equations constitute a tridiagonal matrix of the following form:

$$\begin{array}{lllll}
B_1T_1 + C_1T_2 & & & & = D_1 \\
A_2T_1 + B_2T_2 + C_2T_3 & & & & = D_2 \\
\quad A_3T_2 + B_3T_3 + C_3T_4 & & & & = D_3 \\
\quad\quad \vdots \quad\quad \vdots & & & & \quad\vdots \\
 & & & A_NT_{N-1} + B_NT_N & = D_N
\end{array}$$

Gauss' elimination method, as discussed in reference 4, is applied to solve the system of equations. This method affords a fast and accurate solution for matrices containing a dominant diagonal. The solution of this matrix gives the temperature of each node in the system for the next future time step. The entire process is repeated for each time step throughout the run, giving a time history of the temperature at each node.

Using this method of solution, residual errors in the temperature computations at the beginning of the time step are distributed throughout the entire system of nodal equations and tend to cancel out rapidly. The principle advantage in using the implicit method is a set of equations that are mathematically stable in time and distance. Therefore, the magnitude of the time step is not limited by a convergence criteria. However, care must be taken in selecting the magnitude of the time step in order to minimize truncation errors when the second derivative of temperature with respect to time is large. A similar approach is used to minimize truncation errors in distance by choosing small node dimensions in locations where large second derivatives of temperature with respect to distance are expected.

In the case of a char forming ablative heat shield where approximately 80 percent of the heat is reradiated, instability can arise in taking large time steps such that the temperature of the surface node can start oscillating on successive time steps on achieving a balance between the radiation source and sink. Therefore, in ablation problems in which the surface node loses a large percentage of heat by radiation, oscillations of the node can be damped out by taking small time steps during conditions of high heat flux and near radiation equilibrium temperatures.

ANALYSIS

Figure 2 is a schematic of the thermal protection system that is to be analyzed. A receding surface has been assumed with the formation of a residual char layer and reaction zone. The thermal protection system is composed of 1 charring material and a maximum of 12 different backup materials with or without air gaps. The analysis is such that the entire system may be composed of noncharring materials. The thermal properties of all materials are temperature dependent; also, the charring material properties are state dependent (fully or partially charred).

The response of charring ablation heat shields to a hyperthermal environment is extremely complex, and simplifying assumptions and approximations are necessary to afford a numerical solution. The following assumptions and approximations are utilized in the equations developed in this report:

a. The material decomposes from the virgin state to a porous char layer in the reaction zone.

b. The reaction zone can be defined by an upper and lower temperature limit.

c. The gas generated within the reaction zone is assumed to pass out of the structure with no pressure loss. No gas accumulation within a node is allowed.

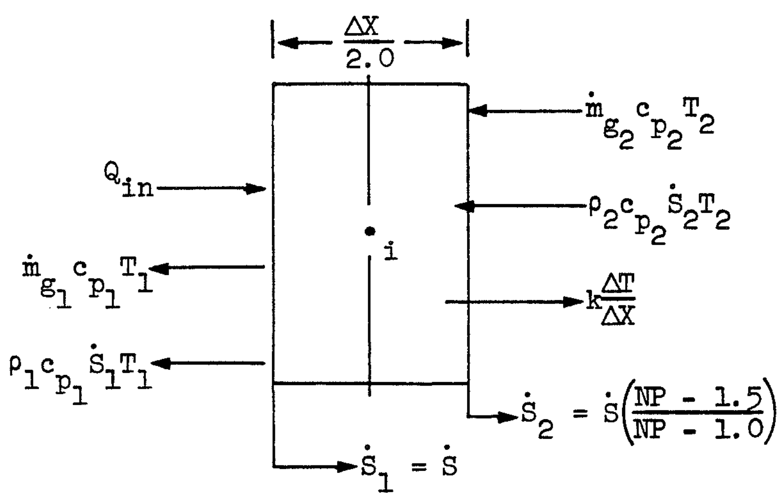
d. Local thermal equilibrium is maintained between the gas and solid.

e. The gas undergoes no further chemical reaction within the residual material after having been formed.

Derivation of Equations

The equations are derived for a moving boundary coordinate system, where the front face is the moving surface (ref. 5). With this system, the ablating material is divided into a fixed number of nodes with a thickness (ΔX) which depends on the instantaneous location of the front face. The surface recession is handled in a continuous manner eliminating the need of throwing away or lumping off of nodes.

The physical model for the front surface including all heating terms is shown below



The energy equation at the front char surface is:

$$\frac{d}{d\theta}\left(\frac{1}{2}\,\Delta X\,\rho_1 c_{p_1} T_1\right) = \frac{1}{2}\,\Delta X\,\rho_1 c_{p_1}\frac{dT_1}{d\theta} + \frac{1}{2}\,\rho_1 c_{p_1} T_1 \frac{d(\Delta X)}{d\theta}$$

$$= Q_{in} + \dot{m}_{g_2} c_{p_2} T_2' + \rho_2 \dot{S}_2 c_{p_2} T_2' - \dot{m}_{g_1} c_{p_1} T_1'$$

$$- \rho_1 c_{p_1} \dot{S}_1 T_1' - k_{1-2}\left(\frac{\Delta T}{\Delta X}\right) \tag{12}$$

where

$$Q_{in} = \dot{q}_{c\ Blow} + \dot{q}_{rad} + \dot{q}_{comb} - F\epsilon\sigma\left(T_1^{\,4} - T_\infty^{\,4}\right)$$

and

$$\frac{d(\Delta X)}{d\theta} = \frac{d}{d\theta}\left(\frac{VL - S}{NP - 1}\right) = -\frac{\dot{S}}{NP - 1}$$

where $\dot{S}$ is the linear surface recession rate, NP the total number of nodes in the ablation material of thickness VL.

Rewriting equation (12) in implicit finite difference form:

$$Q_{in} + \dot{m}_{g_2} c_{p_2} T_2' - \dot{m}_{g_1} c_{p_1} T_1' - \dot{S}\rho_1 c_{p_1} T_1' - \frac{\left(T_1' - T_2'\right)}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}}$$

$$+ \rho_2 c_{p_2} \dot{S}\left(\frac{NP - 1.5}{NP - 1.0}\right) T_2' = \rho_1 c_{p_1} \frac{\Delta X}{2}\left(\frac{T_1' - T_1}{\Delta\theta}\right)$$

$$- \frac{1}{2}\rho_1 c_{p_1} T_1' \left(\frac{\dot{S}}{NP - 1}\right) \qquad (12a)$$

Rearranging and collecting terms:

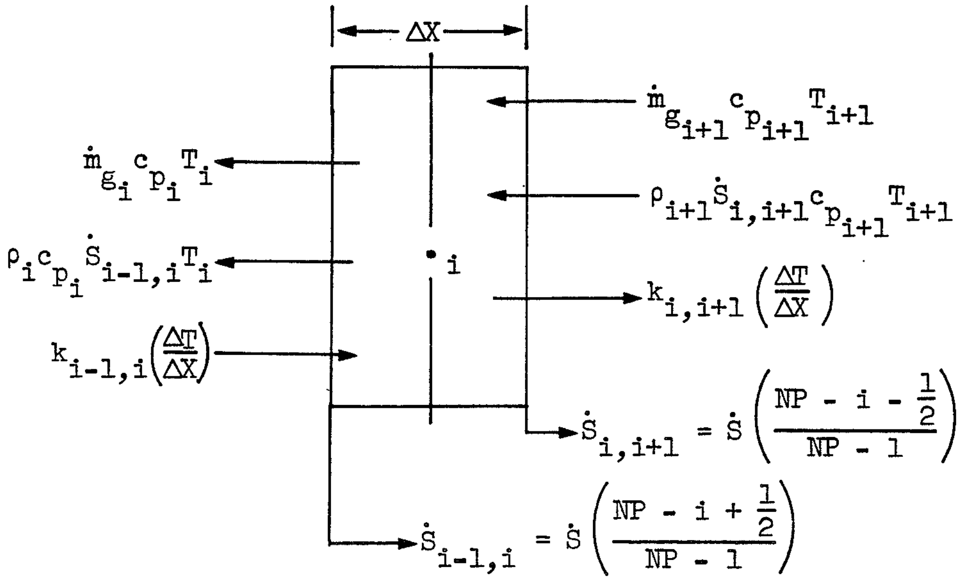
$$-\left(\dot{m}_{g_1} c_{p_1} + \dot{S}\rho_1 c_{p_1} + \rho_1 c_{p_1} \frac{\Delta X}{2\Delta\theta} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} - \frac{1}{2}\rho_1 c_{p_1}\left(\frac{\dot{S}}{NP - 1}\right)\right) T_1'$$

$$+ \left(\dot{m}_{g_2} c_{p_2} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} + \rho_2 c_{p_2} \dot{S}\left(\frac{NP - 1.5}{NP - 1.0}\right)\right) T_2'$$

$$= -\rho_1 c_{p_1} \frac{\Delta X}{2\Delta\theta} T_1 - Q_{in}$$

(12b)

The physical model for interior points in the mature char zone, including all heating terms, is shown below:



The energy equation for interior points in the char matrix is:

$$\frac{d}{d\theta}\left(\Delta X_i \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i' \left(\frac{\dot{S}}{NP - 1}\right)$$

$$= \dot{m}_{g_{i+1}} c_{p_{i+1}} T_{i+1}' + k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T_{i+1}'$$

$$- k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \tag{13}$$

Putting equation (13) in an implicit finite difference form:

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right) T'_{i-1} - \left(\dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left(\frac{\dot{S}}{NP - 1}\right)\right) T'_i$$

$$+ \left(\dot{m}_{g_{i+1}} c_{p_{i+1}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right) T'_{i+1}$$

$$= -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i \tag{13a}$$

NOTE: In the mature char zone, no internal gaseous ablation products are assumed to form. The reaction zone is the source for the formation of the internal gaseous products. Therefore, in equations (12) and (13), $\dot{m}_{g_i} = \dot{m}_{g_{i+1}}$.

The physical model for nodes in the reaction zone is identical to schematic shown for the interior nodes in the char except for considering the energy absorbed in formation of the gaseous ablation products. The heat balance equation for a node in the reaction zone is:

$$\frac{d}{d\theta}\left(\Delta X \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T'_i \left(\frac{\dot{S}}{NP - 1}\right) - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}}\right) H_d$$

$$= \dot{m}_{g_{i+1}} c_{p_{i+1}} T'_{i+1} + k_{i-1,i} \left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T'_{i+1}$$

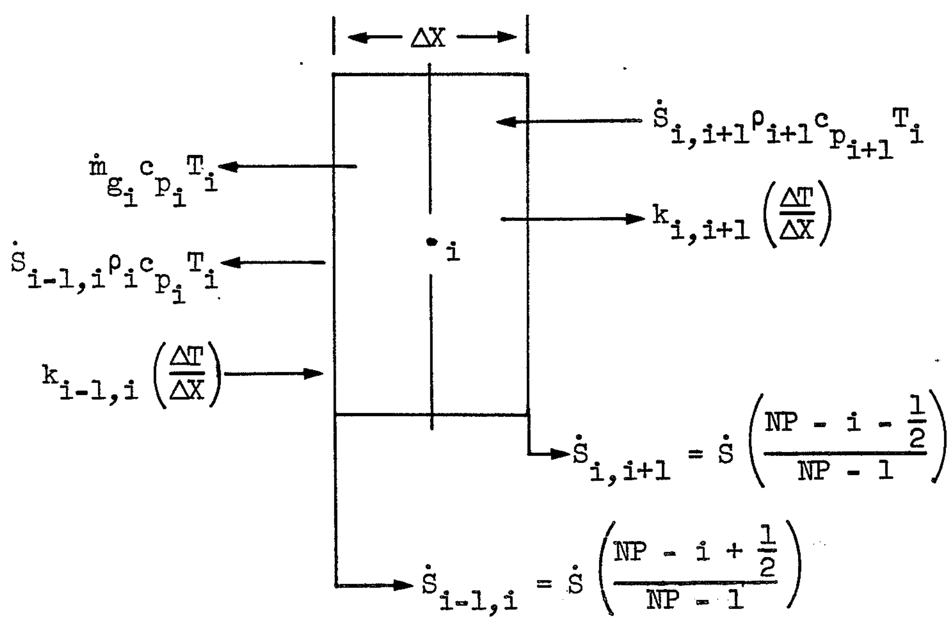
$$- k_{i,i+1} \left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T'_i - \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T'_i \tag{14}$$

rearranging:

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left(\dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{S} \left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left(\frac{\dot{S}}{NP - 1}\right)\right) T'_i + \left(\dot{m}_{g_{i+1}} c_{p_{i+1}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right) T'_{i+1}$$

$$= -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i - \left(\dot{m}_{g_i} - \dot{m}_{g_{i+1}}\right) H_d \qquad (14a)$$

The physical model for the interface between the reaction zone and virgin material is illustrated below:



The heat balance equation for this node is:

$$\frac{d}{d\theta}\left(\Delta X\rho_i c_{p_i} T_i\right) = \Delta X\rho_i c_{p_i}\frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i'\left(\frac{\dot{S}}{NP - 1}\right) - \dot{m}_{g_i} H_d$$

$$= k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}}\dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T_{i+1}'$$

$$- k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right) - \dot{m}_{g_i} c_{p_i} T_i' - \rho_i c_{p_i}\dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i'$$

(15)

Rearranging:

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right) T_{i-1}' - \left(\dot{m}_{g_i} c_{p_i} + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right.$$

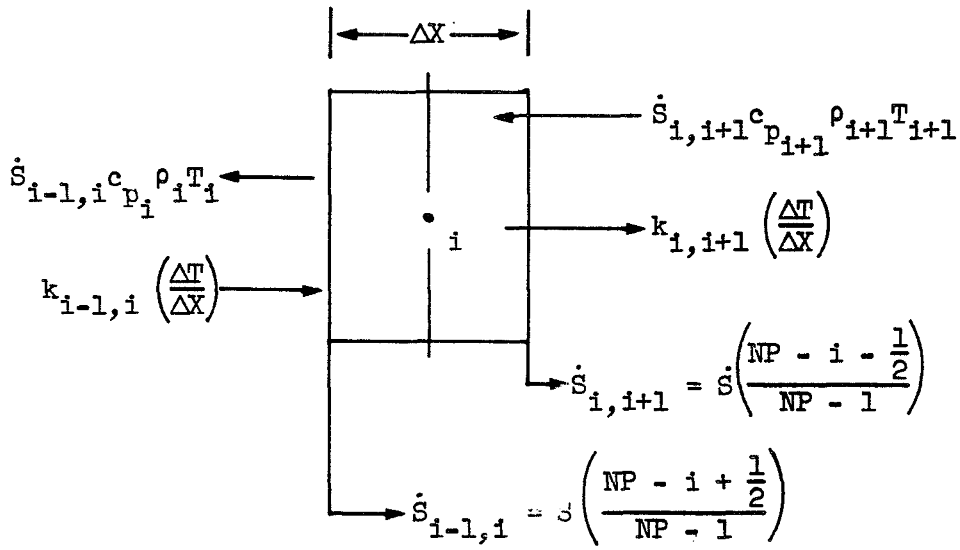
$$\left. + \rho_i c_{p_i}\dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right) T_i'$$

$$+ \left(\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}}\dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right) T_{i+1}'$$

$$= -\rho_i c_{p_i}\frac{\Delta X}{\Delta\theta} T_i - \dot{m}_{g_i} H_d$$

(15a)

The physical model for an interior node in the virgin material is:



The heat balance for this nonablating node is:

$$\frac{d}{d\theta}\left(\Delta X \rho_i c_{p_i} T_i\right) = \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T_i' \left(\frac{\dot{S}}{NP - 1}\right)$$

$$= k_{i-1,i}\left(\frac{\Delta T}{\Delta X}\right) + \rho_{i+1} c_{p_{i+1}} \dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right) T_{i+1}' - k_{i,i+1}\left(\frac{\Delta T}{\Delta X}\right)$$

$$- \rho_i c_{p_i} \dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) T_i' \qquad (16)$$

Rearranging:

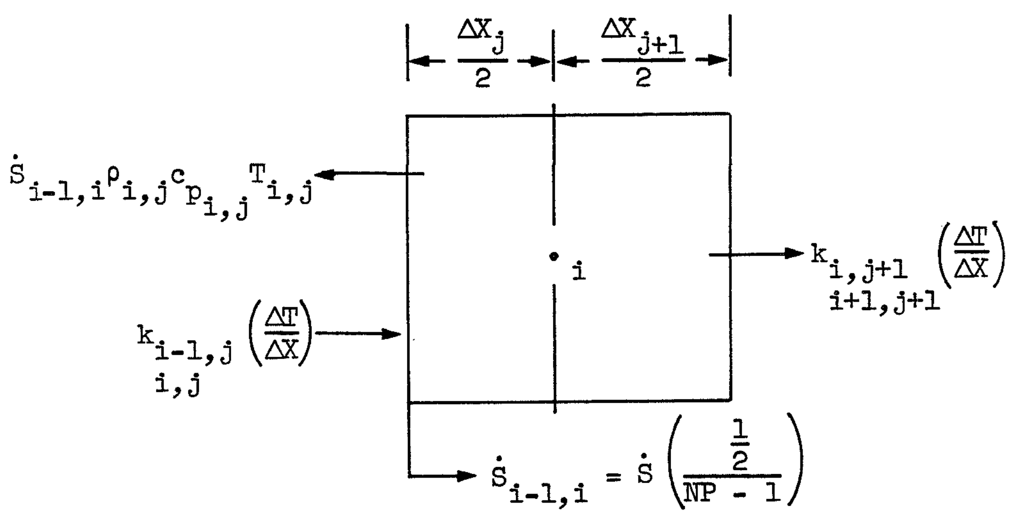
$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left(\frac{1}{\frac{\Delta X}{2k_{i-1}}+\frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}}\right.$$

$$\left. + \rho_i c_{p_i}\dot{S}\left(\frac{NP - i + \frac{1}{2}}{NP - 1}\right) + \rho_i c_{p_i}\frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i}\left(\frac{\dot{S}}{NP - 1}\right)\right)T'_i$$

$$+ \left(\frac{1}{\frac{\Delta X}{2k_i}+\frac{\Delta X}{2k_{i+1}}} + \rho_{i+1}c_{p_{i+1}}\dot{S}\left(\frac{NP - i - \frac{1}{2}}{NP - 1}\right)\right)T'_{i+1} = -\rho_i c_{p_i}\frac{\Delta X}{\Delta \theta}T_i$$

(16a)

The physical model for the last node in the ablation material and first node in the backup structure is:



The heat balance equation for this node:

$$\frac{d}{d\theta}\left(\left(\frac{\Delta X_j}{2}\rho_{i,j}c_{p_{i,j}} + \frac{\Delta X_{j+1}}{2}c_{p_{i,j+1}}\rho_{i,j+1}\right)T_i\right)$$

$$= \left(\frac{\Delta X_j\rho_{i,j}c_{p_{i,j}} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2}\right)\frac{dT}{d\theta} - \frac{1}{2}\left(\frac{\dot{S}}{NP - 1}\right)c_{p_{i,j}}\rho_{i,j}T_i'$$

$$= k_{\substack{i-1,j\\i,j}}\left(\frac{\Delta T}{\Delta X}\right) - c_{p_{i,j}}\rho_{i,j}\dot{S}\left(\frac{\frac{1}{2}}{NP - 1}\right)T_i' - k_{\substack{i,j+1\\i+1,j+1}}\left(\frac{\Delta T}{\Delta X}\right) \tag{17}$$

Rearranging:

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T_{i-1}' - \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right.$$

$$\left.+\left(\frac{\Delta X_j\rho_{i,j}c_{p_{i,j}} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2}\right)\right)T_i' + \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right)T_{i+1}'$$

$$= -\left(\frac{\Delta X_j c_{p_{i,j}}\rho_{i,j} + \Delta X_{j+1}c_{p_{i,j+1}}\rho_{i,j+1}}{2}\right)T_i \tag{17a}$$

The backup structure may contain up to a maximum of 12 different materials with or without air gaps between materials. Therefore, conduction or radiation and/or convection between materials is allowed. The heat balance equations for the various modes of heat transfer in the back backup structure are now presented:

a. Interior node material:

$$\frac{\left(T'_{i-1,j} - T'_{i,j}\right)}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} - \frac{\left(T'_{i,j} - T'_{i+1,j}\right)}{\frac{\Delta X}{2k_{i,j}} + \frac{\Delta X}{2k_{i+1,j}}} = \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta\theta} \left(T'_{i,j} - T_{i,j}\right) \tag{18}$$

Rearranging:

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) T'_{i-1,j} - \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_j}{2k_{i,j}} + \frac{\Delta X_j}{2k_{i+1,j}}} + \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta\theta}\right) T'_{i,j} + \left(\frac{1}{\frac{\Delta X_j}{2k_{i,j}} + \frac{\Delta X_j}{2k_{i+1,j}}}\right) T'_{i+1,j}$$

$$= -\rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta\theta} T_{i,j} \tag{18a}$$

b. First node of two interior materials with <u>no</u> gap:

$$\frac{\left(T'_{i-1,j} - T'_{i,j}\right)}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} - \frac{\left(T'_{i,j+1} - T'_{i+1,j+1}\right)}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}$$

$$= \left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + \rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2}\right) \left(T'_{i,j} - T_{i,j}\right) \tag{19}$$

NOTE: $T'_{i,j} = T'_{i,j+1}$ for this case.

Rearranging:

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) T'_{i-1,j} - \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} + \left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + \rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2.0}\right)\right) T'_{i,j}$$

$$+ \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right) T'_{i+1,j+1}$$

$$= -\left(\frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + c_{p_{i,j+1}} \rho_{i,j+1} \Delta X_{j+1}}{2.0}\right) T_{i,j} \tag{19a}$$

c. First node of interior material with an air gap between materials:

$$h_j\left(T'_{i-1,j} - T'_{i,j+1}\right) + \left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T'^{4}_{i-1,j} - T'^{4}_{i,j+1}\right)$$

$$-\left(\frac{T'_{i,j+1} - T'_{i+1,j+1}}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right) = \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\Delta\theta}\left(T'_{i,j+1} - T_{i,j+1}\right) \tag{20}$$

Equation (20) may be linearized using the approximation

$$T'^{4} \cong 4T^3 T' - 3T^4$$

as discussed in the Program Description section.

Therefore, rearranging and linearizing, equation (20) becomes:

$$\left(h_j + \left(\frac{4\sigma T^3_{i-1,j}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right)T'_{i-1,j} - \left(h_j + \left(\frac{4\sigma T^3_{i,j+1}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right.$$

$$\left. + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} + \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\Delta\theta}\right) T'_{i,j+1}$$

$$- \left(\frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}}\right) T'_{i+1,j+1}$$

$$= - \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2\Delta\theta} T_{i,j+1}$$

$$- \left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T^4_{i,j+1} - T^4_{i-1,j}\right) \tag{20a}$$

d. <u>Last node</u> of an interior material <u>with an air gap</u> between materials:

$$\frac{\left(T'_{i-1,j} - T'_{i,j}\right)}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} - h_j\left(T'_{i,j} - T'_{i,j+1}\right)$$

$$- \left(\frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T'^4_{i,j} - T'^4_{i,j+1}\right) = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \tag{21}$$

Rearranging and linearizing:

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) T'_{i-1,j} - \left(h_j + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \left(\frac{4\sigma T^3_{i,j}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right.$$

$$\left. + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\Delta\theta}\right) T'_{i,j} + \left(h_j + \left(\frac{4\sigma T^3_{i,j+1}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\right) T'_{i,j+1}$$

$$= - \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\Delta\theta} T_i + \left(\frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1}\right)\left(T^4_{i,j+1} - T^4_{i,j}\right) \tag{21a}$$

e. Final node in backup structure:

(1) Adiabatic surface

$$\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \tag{22}$$

Rearranging:

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) T'_{i-1,j} - \left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right.$$

$$\left. + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\Delta\theta}\right) T'_{i,j} = - \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2\Delta\theta} T_{i,j} \tag{22a}$$

(2) Radiation and/or convection loss to cabin environment

$$\left(\frac{T'_{i-1,j} - T'_{i,j}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right) - h_{env}\left(T'_{i,j} - T_{env}\right)$$

$$- F_{env}\sigma\left(T'^{4}_{i,j} - T^{4}_{env}\right) = \frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j}{2\Delta\theta}\left(T'_{i,j} - T_{i,j}\right) \qquad (23)$$

Rearranging:

$$\left(\frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}}\right)T'_{i-1,j} - \left(h_{env} + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + F_{env}\sigma 4T^3_{i,j}\right.$$

$$\left. + \frac{\rho_{i,j}c_{p_{i,j}}\Delta X_j}{2\Delta\theta}\right)T'_{i,j} = - \frac{\rho_{i,j}c_{p_{i,j}}\Delta X_k}{2\Delta\theta}T_{i,j}$$

$$- h_{env}T_{env} - F_{env}\sigma\left(3T^4_{i,j} + T^4_{env}\right)$$

$$(23a)$$

Discussion of Assumptions

A brief discussion of several assumptions and approximations made in deriving the heat balance equations is now presented.

As shown in the Derivation of Equations section, transient heat conduction, thermal degradation, and the flow of the gaseous products from the reaction zone are the internal thermal transport phenomena of interest. Several methods are available in the treatment of the thermal decomposition process and they differ primarily in whether the chemical decomposition occurs in a single plane at a fixed temperature or a spacially continuous decomposition in depth is assumed. This analysis assumes that the decomposition from the virgin to the char state occurs in a reaction zone that is defined by known temperature limits. These temperature limits are determined from thermogravimetric (TGA) test data for the particular material being investigated. Figure 3 is a TGA curve for typical charring ablation material. From this curve, the rate of pyrolysis $\left(\dot{m}_g\right)$ is calculated by knowing the temperature change of a particular node with time, that is,

$$\dot{\rho}_i = \frac{\rho_i' - \rho_i}{\Delta\theta} \tag{24}$$

$$\dot{m}_{g_i} = \sum_{i}^{NP} \dot{\rho}_i \Delta X_i \tag{25}$$

This method of computing the gas generation rates and local instantaneous density may be subject to error since the TGA curve of a material is influenced by temperature rise rate (DEG/SEC) and the reaction zone may shift up and down the temperature scale. This error can be eliminated by the use of an Arrhenius expression of the form

$$\frac{d\rho}{d\theta} = -A\left(\rho - \rho_c\right)^n \rho^{-\frac{E}{RT}} \tag{26}$$

The method now being used in STAB II (equation (25)) to calculate the pyrolysis rate is being investigated to determine its validity. The final formulation of the pyrolysis rate law must rest heavily on the experimental rate data for the material under investigation. The use of simple expressions such as equations (24) and (25) may be entirely adequate depending upon activation energy for the decomposition process and order of reaction.

The aerodynamic heating input in the analysis consists of convective and radiative components treated separately. This distinction is necessary since the convective heating can be significantly reduced due to the injection of the ablation gases into the boundary layer with generally no effect on radiant heating. Reduction in the convective heating rate can be approximated by the following expression (ref. 6)

$$\dot{q}_{Block} \equiv \eta \dot{m}_g\left(H_T - H_w\right) \tag{27}$$

Therefore,

$$\dot{q}_{Blow} = \dot{q}_{cw} \left(\frac{H_T - H_w}{H_T - H_{300}} \right) - \dot{q}_{Block} \tag{28}$$

However, equation (28) is unsatisfactory for high blowing rates, since $\dot{q}_{Block}$ can become greater than $\dot{q}_{cw}$. An experimental curve of blocking effectiveness $\psi \left(\frac{\dot{q}}{\dot{q}_{cw}} \right)$ as a function of the mass transfer parameter $\frac{\dot{m} H_T}{\dot{q}_{cw}}$ can be employed to determine the heating reduction at high blowing rates. Both methods have been employed in the STAB II analysis. Equation (28) is presently in use. However, no satisfactory method for accurately predicting the convective heat blockage has been determined.

Another source of heating is the combustion of the ablation products in the boundary layer. Reference 7 presents an analysis of the oxidation of a carbon surface and the resulting combustive heating. The heating due to combustion as derived in reference 7 is

$$\dot{q}_{comb} = \dot{m}_c \, \Delta H_c \tag{29}$$

where ΔH_c is the heat of combustion per unit weight of char.

The thermal properties of the ablation material are both temperature and state dependent (fully or partially charred). Figure 4 is an illustration of the variation of these properties with temperature and state. The thermal properties are assumed to vary as follows:

a. Char zone $\left(T_i \geq T_{CHAR} \right)$

$$k_c = f \text{ (temp)}$$

$$c_{p_c} = f \text{ (temp)}$$

$$\rho_c = \text{constant}$$

b. Reaction zone $\left(T_{ABL} \leq T_i < T_{CHAR} \right)$

$$\rho = f \text{ (temp)} = \rho_v + \left(\rho_v - \rho_c \right) \left(\frac{T_i - T_{ABL}}{T_{ABL} - T_{CHAR}} \right)$$

$$k = f(\rho) = k_c + \left(k_v - k_c\right)\left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c}\right)$$

$$c_p = f(\rho) = c_{p_c} + \left(c_{p_v} - c_{p_c}\right)\left(\frac{\rho_i - \rho_c}{\rho_v - \rho_c}\right)$$

c. Virgin zone $\left(T_i < T_{ABL}\right)$

$$\rho_v = \text{constant}$$

$$k_v = f\ (\text{temp})$$

$$c_{p_v} = f\ (\text{temp})$$

The calculation of char removal, due to chemical, thermal, mechanical, or by combination of these mechanisms, has been examined by a multitude of investigators and numerous correlations exist, depending on the specific material involved.

To provide a maximum degree of flexibility for analyzing both ground and flight test data and systhesizing trajectories, the following provisions for char removal (surface movement) are provided:

a. Removal of char as a function of surface temperature.

b. Removal of char at a rate which is a function of time.

As the char is removed, the surface moves with respect to a coordinate fixed in the material. The distance between the initial surface location and the char surface is

$$S = \int_0^\theta \dot{S}\ d\theta$$

CUSTOMER UTILIZATION INSTRUCTIONS

Introduction

IBM 7094/40 program F021, standard ablation program, designated STAB II, is designed to evaluate the transient thermal performance of a charring ablation heat protection system. The program considers 1 ablating material and up to 12 different materials in the supporting backup structure. A maximum of 50 nodes may be considered in the ablation material and a maximum of 10 nodes per material is allowed for each backup structure material. Air gaps can be considered between successive materials in the backup, thus allowing for both radiative and/or convective heat transfer between materials. The heat loss to the cabin environment from the backup structure can be accomplished by both radiation and/or convection or an adiabatic backface surface may be prescribed.

Unless otherwise specified, the input problem data is in "floating point" form (E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. It is suggested that each floating point number have a sign, a two-digit exponent, and a decimal point. For example, the number 145.23 can be written as +1.4523 +02, +145.23 +00, or +14523 +03

Input Nomenclature

The nomenclature used in the problem data input is as follows:

NCASE number of problems to be run successively

HEAD any 72 alphabetical and/or numerical characters

TITLE control card for reading in new input for successive problems

1. blank card – new data will be read in

2. 6 asterisks in columns 1 to 6. Skip to next read statement

TLIM time limit of problem, sec

TINT starting time of problem, sec

NPTT number of points in time-step table (the minimum value of NPTT is 2)

NPLØT output plot control

=1 plot routine will be used

=0 plot routine will be ignored

TTABLE time in time-step table, sec

DELTT	time step to be used for each calculation – starting at time TTABLE, sec
IPRC	variable print frequency in TTABLE table; that is, if DELTT = 1.0 and IPRC = 10, the output will be printed at 10-second intervals
FCØNV	factor to correct convective heating rate for various body locations
FRAD	factor to correct radiative heating for various body locations
TABL	temperature at which ablation starts, °R
TCHAR	temperature at which ablation stops, °R
TREC	surface temperature, (°R) <u>or</u> time (second) at which char removal is to start
RHØV	density of virgin ablation material, lb/ft^3
RHØC	density of mature char material, lb/ft^3
FBLØW	blowing efficiency of ablation gases in reducing convective heating
EMV	emissivity of virgin ablation material
EMC	emissivity of charred ablation material
H300	enthalpy of air at 300° K, 129.06 Btu/lb_m
VL	initial thickness of virgin ablation material, in.
HV	heat of degradation of virgin material, Btu/lb_m
VPT	test to determine if the reaction zone and char zone thermal properties are irreversible with temperature
=0	properties are irreversible and equal to the value at the maximum individual node temperature (this is the recommended value for VPT)
=1	properties are reversible
FV	view factor for external environment

TV	sink temperature of external environment, °R
CHARK	thermal conductivity of material at TCHAR, Btu/hr-ft-°R
CHARC	specific heat of material at TCHAR, Btu/lb_m-°R
ABLK	thermal conductivity of material at TABL, Btu/hr-ft-°R
ABLC	specific heat of material at TABL, Btu/lb_m-°R
NP	number of node points in ablation material
NKC	number of points in char thermal conductivity – temperature table
NCPC	number of points in char specific heat – temperature table
NKV	number of points in virgin thermal conductivity – temperature table
NCPV	number of points in virgin specific heat – temperature table
NREC	number of points in surface recession – temperature <u>or</u> time table
TKC	temperature values in char thermal conductivity – temperature table, °R
XKC	thermal conductivity values in char thermal conductivity – temperature table, Btu/ft-hr-°R
TCPC	temperature values in char specific heat – temperature table, °R
CPC	specific heat values in char specific heat – temperature table, Btu/lb_m-°R
TKV	temperature values in virgin thermal conductivity – temperature table, °R
XKV	thermal conductivity values in virgin thermal conductivity – temperature table, Btu/ft-hr-°R
TCPV	temperature values in virgin specific heat – temperature table, °R

CPV	specific heat values in virgin specific heat temperature table, Btu/lb_m-°R
TS	temperature (°R) or time (sec) values in the surface recession table
SR	surface recession values in the surface recession – temperature or time table, in./sec
NTRAPT	number of time points in the trajectory input table
TIME	the array of (NTRAPT) trajectory time values, sec
QCØN	the corresponding array of cold wall convective heating rates, Btu/ft^2-sec
QRAD	the corresponding array of radiative heating rates, Btu/ft^2-sec
VEL	the corresponding array of flight velocity, ft/sec
NMB	number of materials in backup structure
NPBS	total number of node points in backup structure
BL	total thickness of backup structure, in.
XNPM	number of nodes in <u>each individual</u> material in backup structure
NKPB	number of points in <u>each individual</u> backup structure material thermal conductivity – temperature table
NCPB	number of points in <u>each individual</u> backup structure material specific heat – temperature table
XIDNT	any 72 alphanumeric characters used to describe <u>each individual</u> material in the backup structure
TXK	temperature values in backup material thermal conductivity – temperature tables, °R
XK	thermal conductivity values in backup material thermal conductivity – temperature tables, Btu/ft-hr-°R

TCP — temperature values in backup material specific heat - temperature tables, °R

CPX — specific heat values in backup material specific heat - temperature tables, Btu/lb_m-°R

RHØBX — density of individual materials in backup, lb/ft^3

XBM — thickness of individual materials in backup, in.

EMFB — emissivity of front surface of each material in backup

EMBB — emissivity of back surface of each material in backup

H — film coefficient between adjacent materials in backup, Btu/hr-ft^2-°R

GAPX — width of gap between adjacent materials in backup, in.

FTEST, BTEST — tests to determine the mode of heat transfer between materials for the front and backface of each material respectively

- =0 — conduction only between materials
- =+1 — convective heat transfer only
- =-1 — radiation only or radiation and convection heat transfer

TENV — temperature of interior cabin environment, °R

HENV — film coefficient to interior cabin environment, Btu/ft^2-hr-°R

FENV — view factor and emissivity product for radiative heat transfer to cabin interior

QLØSS — boundary condition between last node of the backup structure and cabin environment

- =0 — adiabatic surfaces
- =+1 — radiation and/or convective loss

TEST2 determines the proper heat shield initial temperature distribution

=0 constant, uniform initial temperature distribution

=-1 arbitrary initial temperature distribution

=+1 linear temperature distribution

TEMPI temperature to be used when constant temperature distribution option is used, °R

TXØ initial temperature at front surface of heat shield to be used in computing initial linear temperature gradient, °R

TEMDI arbitrary temperature distribution values, to be used only if TEST2 is negative. R

NHP number of points in enthalpy – temperature curve fit

HX enthalpy values in enthalpy – temperature table, Btu/lb_m

TW corresponding temperature values in enthalpy – temperature table, °R

NOTE: This table is used for computing the wall enthalpy. An input deck for NHP, HX, and TW has been prepared for air and is available upon request.

Input Data Card Preparation

The input data are given in the following order. Each number below refers to a separate record and must begin on a new data card. The input data has been grouped, where possible, into various sections dealing with a particular part of the input, that is, ablation material properties, trajectory data, backup structure, et cetera. This permits the use of a minimum number of input cards for running successive problems. The title card as described in the input nomenclature controls the input for successive problems.

1. The first data card contains the value of NCASE. NCASE is an integer (I5 format) and must end in column 5. This card tells how many problems are to be run and is entered only <u>once</u> at the start of the data deck.

2. Columns 1 through 72 of the second data card contain any title or identification information desired — any alphanumeric character may be used. This card will be printed at the top of the first page of the output. This card <u>must</u> be included in all successive problems to be run.

a. Problem Time Section

3. TITLE card — if blank, the following 2 cards must be submitted; if 6 asterisks are punched in columns 1 through 6, skip to record number 6.

4. This record contains, in the following order: TLIM, TINT, NPTT, NPLØT. TLIM and TINT are entered as floating point numbers and must end in columns 12 and 24. NPTT and NPLØT are integers entered with an I5 format and must end in columns 30 and 35.

5. Start entering the values of TTABLE, DELTT, IPRC. TTABLE and DELTT are floating point numbers and must end in columns 12 and 24. IPRC is entered as integer with an I5 format and must end in column 30. Use as many cards as required to enter NPTT values.

b. Heating Rate Factors Section

6. TITLE card — if blank, the following card must be submitted; if 6 asterisks are punched in columns 1 through 6, skip to record number 8.

7. Enter the following: FCØNV, FRAD. These numbers are entered as floating point numbers and must end in columns 12 and 24.

c. Ablation Material Section

8. TITLE card — if blank, the following cards 9 through 18 must be submitted; if 6 asterisks are punched in columns 1 through 6, skip to record number 19.

9. HEADNG card — any alphanumeric characters in columns 1 through 72. Records 9 through 18 contain input data for the ablation material.

10. Enter the following: TABL, TCHAR, TREC, RHØV, RHØC, FBLØW. These numbers are entered as floating point numbers (6E12.8 format) must end in columns 12, 24, 36, 48, 60 and 72.

11. Enter the following: EMV, EMC, H300, VL, HV, VPT. Use same format as card 10.

12. Enter the following: FV, TV, CHARK, CHARC, ABLK, ABLC. Use same format as card 10.

13. This card contains, in the following order: NP, NKC, NCPC, NKV, NCPV, NREC. These numbers are fixed point integers and must end in columns 5, 10, 15, 20, 25, and 30. An I5 format is used to read in these numbers.

14. Start entering the curve of TKC versus XKC, with the values of TKC ending in columns 12, 36, and 60. The corresponding values of XKC must end in columns 24, 48, and 72; for example, three TKC-XKC points are contained on one card. The numbers are entered as floating point numbers. Use as many cards as required to enter NKC points on the curve.

15. Start entering the curve of TCPC versus CPC with the values of TCPC, ending in columns 12, 36, and 60. The corresponding values of CPC must end in columns 24, 48, and 72; for example, three TCPC-CPC points are contained on one card. The numbers are entered as floating point numbers. Use as many cards as required to enter NCPC points on the curve.

16. Start entering the curve of TKV versus XKV with the values of TKV ending in columns 12, 36, and 60. The corresponding values of XKV must end in columns 24, 48, and 72; for example, three TKV-XKV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter the NKV points on the curve.

17. Start entering the curve of TCPV versus CPV with the values of TCPV, ending in columns 12, 36, and 60. The corresponding values of CPV must end in columns 24, 48, and 72; for example, three TCPV-CPV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPV points on the curve.

18. Start entering the curve of TS versus SR with the values of TS, ending in columns 12, 36, and 60. The corresponding values of SR must end in columns 24, 48, and 72; for example, three TS-SR points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NREC points on the curve.

d. Trajectory Data Section

19. TITLE card – if blank, the following cards 20 through 22 must be submitted; if 6 asterisks are punched in columns 1 through 6, skip to record number 23.

20. HEADNG card – any alphanumeric characters in columns 1 through 72. Records 21 through 22 contain trajectory input data.

21. Enter the following: NTRAPT. This number is an integer and must end in column 5. An I5 format is used to read in this number.

22. Start entering the trajectory data in the following order: TIME, QCØN, QRAD, VEL. These values are entered as floating point numbers and must end in columns 12, 24, 36, and 48. There are four trajectory data points on one card. Use as many cards as required to enter NTRAPT points in the trajectory.

e. Backup Structure Section

23. TITLE card – if blank, the following cards 24 through 32 must be submitted; if 6 asterisks are punched in columns 1 through 6, skip to record number 33.

24. HEADNG card – any alphanumeric characters in columns 1 through 72. Records 25 through 32 contain properties of backup structure.

25. Enter the following: NMB, NPBS, BL. These three values must end in columns 5, 10 and 24. NMB and NPBS are integers and are read in under an I5 format. BL is a floating point number.

26. Enter the values of XNPM. XNPM is in floating point form and must end in columns 12, 24, 36, 48, 60 and 72. Use as many cards as required to enter NMB points.

27. Enter the values of NKPB and NCPB. These numbers are integers and NKPB must end in columns 5, 15, 25, 35, and 45; and the corresponding values of NCPB must end in columns 10, 20, 30, 40, and 50. An I5 format is used to read these values. Five NKPB-NCPB values are contained on one card. Use as many cards as are required to enter NMB points.

28. XIDNT card – any alphanumeric characters in columns 1 through 72. This card contains a description of each backup material.

29. Start entering the curve of TXK versus XK with the values of TXK, ending in columns 12, 36, and 60. The corresponding values of XK must end in columns 24, 48, and 72; for example, three TXK-XK points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NKPB points on the curve.

30. Start entering the curve of TCP versus CPX with the values of TCP, ending in columns 12, 36, and 60. The corresponding values of CPX must end in columns 24, 48, and 72; for example, three TCP-CPX points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPB points on the curve.

NOTE: Repeat records 28, 29, and 30 until the properties for NMB materials have been entered. The maximum number for NMB is 12.

31. Start entering the following values in order: RHØBX, XBM, EMFB, EMBB. These values are entered as floating point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

32. Start entering the following values in order: H, GAPX, FTEST, BTEST. These values are entered as floating point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

f. Interior Environment Section

33. TITLE card – if blank, the following cards 34 through 35 must be submitted; if 6 asterisks are punched in columns 1 through 6, skip to record number 36.

34. HEADNG card – any alphanumeric characters in columns 1 through 72. Record 35 contains properties of environment.

35. Enter the following: TENV, HENV, FENV, QLØSS. The values are entered as floating point numbers and must end in columns 12, 24, 36, and 48.

g. Initial Temperature Section

36. TITLE card – if blank, the following records 37 through 38 must be submitted; if 6 asterisks are punched in columns 1 through 6, skip to record 40.

37. HEADNG card – any alphanumeric characters in columns 1 through 72. Records 38 through 39 contain initial temperature distribution input.

38. Enter the following: TEST2, TEMPI, TXO. These values are entered as floating point numbers and must end in columns 12, 24, and 36.

NOTE: If TEST2 is a negative number, record 39 must be submitted; otherwise, skip to record 40.

39. Enter the arbitrary temperature distribution values, TEMDI. These values are entered as floating points with a 6E12.8 format. Use as many cards as required to enter NP plus NPBS node points.

h. Enthalpy – Temperature Section

40. TITLE card – if blank, the following records 41 and 42 must be submitted; if 6 asterisks are punched in columns 1 through 6, this is the last data card in the problem input.

41. Enter the following: NHP. This value is an integer and must end in column 5. An I5 format is used to read in this number.

42. Start entering the curve of HX versus TW with the value of HX ending in columns 12, 36, and 60. The corresponding values of TW must end in columns 24, 48, and 72; for example, three HX-TW points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NHP points on the curve. Record 42 consists of the last data cards required as input for a problem.

As many successive problems as you wish may be run at one time by proper input preparation. STAB II has been designed to save all input information until changed by new input data. Therefore, the use of the TITLE control card is very important when running more than one problem and using the input data of the previous problem(s). As shown, each input section starts with a TITLE control card for determining whether new input data is to be used. If <u>any data</u> is changed within a section, then <u>all data</u> cards required for that section must be submitted.

STAB II can also be used for solving one dimensional transient heat conduction problems of nonablating materials. The following input parameters must be adhered to:

a. TABL must be greater than the maximum temperature expected during the calculation. Also, TABL > TCHAR > TREC.

b. The ablation material must be considered to be the first material in the structure for calculational purposes.

c. The virgin and char properties must be inputed as described above but can have the same values; that is, XKV = XKC, CPC = CPV, RHØV = RHØC, et cetera.

The following dimensions statements and program limitations should not be violated when preparing the input described above for ablating and nonablating structure:

a. All property tables can have a maximum of 20 points (i.e., a temperature and specific heat value constitute one point).

b. The surface recession table can have a maximum of 50 points (TS and SR constitute one point).

c. The trajectory table can have a maximum of 300 points (TIME, QCØN, QRAD, VEL constitute one point).

d The ablation material can be broken into a maximum of 50 nodes. The backup structure can consist of up to 12 different materials with a maximum of 10 nodes per material.

e. A minimum of 3 nodes per material (ablation or backup) must be specified.

f. A minimum of two materials must be specified (ablation material and one backup structure material).

g. Pure conduction only is allowed between the ablation material and the first material in the backup.

h. If any data input is changed in the Ablation Material Section on successive problems, the Ablation Material Section data cards plus the Initial Temperature Section data cards must be submitted.

Program Output Information

The computed results are available in two forms of output; tabular and plot outputs. The tabular output presents the computed results in block type form for each computation step as controlled by the print count control number. As discussed in the preparation of input data, both the computational time step and print control can be varied throughout the running of a problem. Therefore, excessive printed output is avoided, as well as a considerable savings in actual machine computation time. The plot outputs are printed and plotted only when the entire set of problems to be run are completed.

Tabular output.- The program prints a listing of the data input parameters for identification of the problem and ease in determining if there are any input mistakes. For stacked problems, the program prints only that input information that is changed from the previous problem. The following calculated problem output is printed:

a. Time, sec

b. Cold wall convective heating rate without blowing, Btu/ft^2-sec

c. Radiative heating rate, Btu/ft^2-sec

d. Velocity, ft/sec

e. Gas ablation rate, lb_m/ft^2-hr

f. Char ablation rate, lb_m/ft^2-hr

g. Total ablation rate, lb_m/ft^2-hr

h. Surface recession depth from original surface, in.

i. Hot wall convective heating rate without blowing, Btu/ft^2-sec

j. Temperature distribution in ablation material, °R

k. Temperature distribution in backup structure, °R

The temperatures printed for the ablation material are for fixed distances from the original surface. These distances are calculated from the initial ablation material thickness and number of nodes in ablation material. For example:

let

$$VL = 1.0 \text{ in.}$$

$$NP = 11$$

then

$$\Delta X = \frac{VL}{NP - 1} = 0.1$$

The temperatures will be printed for X distances of 0, 0.1, 0.2, 0.3, et cetera, from the original surface until the surface has receded beyond these fixed distances at which time the node no longer exists and is dropped from the printout. This is illustrated in the following way using the above example; let surface recession = 0.26 in., then the first temperature printed is the surface temperature of the material, located 0.26 in. from the original material surface. The following printed ablation material temperatures are for X distances of 0.3, 0.4, 0.5, ... 1.0 in.

The format for the temperature distribution printout is E16.5 with six temperatures printed per line.

Plot output.- The plot output gives the following ablative material performance parameters as a function of time:

a. Surface depth, in.

b. Bondline temperature between ablator and backup structure, °R

c. Two selected isotherm depths

These values are also printed in tabular form for ease in checking and replotting of the results. The plotted curves contain all maximum and minimum values of the parameters.

PROGRAM VERIFICATION

As discussed in the previous sections, approximations and assumptions were made in the analytical model to afford both a quick and accurate solution in predicting the thermal response of a charring heat shield. These simplifying assumptions and approximations are expected to introduce only minor errors; however, the validity of the analyses and resultant accuracy can be judged only by a comparison with exact theoretical solutions and experimental data. Three examples have been selected and a comparison of the STAB II results with the theoretical and test data is discussed in the following paragraphs.

An elementary transient heating example was chosen to demonstrate the accuracy and numerical stability of the STAB II program. A steel slab 6 inches thick was selected and assumed to be at uniform initial temperature of 460° R (0° F). The thermal properties were considered constant. The front surface was subjected to a heating rate of 72 Btu/sec-ft^2 and an adiabatic back surface was assumed. Figure 5 shows a comparison of the STAB II calculated in depth temperatures as a function of time with the exact solution taken from reference 8.

To demonstrate the STAB II solution with a moving boundary, a slab with constant properties, uniform initial temperature, front surface moving with a constant velocity, and constant surface temperature was chosen. The exact solution for semi-infinite slab with these boundary and initial conditions is presented in reference 9. Figure 6 presents a comparison of the STAB II temperature response with the exact solutions. As can be seen from this figure, the two solutions are not in agreement for approximately the first 50 to 60 seconds of the transient. This disagreement is the result of the quasi-steady state

$$\left(\left(\frac{\partial T}{\partial \theta}\right)_{\xi=0} = 0;\ k\left(\frac{\partial T}{\partial X}\right)_{X=0} = \dot{S}\rho c_p\ \Delta T\right)$$

assumption made in the exact solution analysis. A calculation was made to estimate the induction time (time at which $\frac{\partial T}{\partial \theta} = 0$ is a good assumption) and found to be approximately 60 seconds, which is in agreement with the STAB II results.

Finally, to verify the fully charring ablation model, an example of a typical charring material was chosen. The charring ablation material is initially 1.6 inches thick with an adiabatic back surface and a constant heat flux of 95 Btu/sec-ft^2 applied to the front surface. The surface is assumed to recede at a constant velocity of $3.05\left(10^{-3}\right)$ in./sec. Figure 7 presents a comparison of the in-depth temperatures with actual test results obtained in an arc tunnel. The results are in good agreement, with the largest deviations between calculated and measured values occurring for the thermocouple located 1.0 inches in depth. The disagreement could be attributed to several possible errors; thermal property values, incorrect location of thermocouples, et cetera. The effect of varying the thermal properties (thermal conductivity, specific heat, etc.) is presently being investigated and will be reported in a future report.

Tables I and II present the input and output data used for this example. Figures 8, 9, and 10 are the resulting plot routine output.

The camparisons presented above between the computer results and the exact solutions and test results are considered satisfactory. As discussed previously, the assumptions used in the analytical model will be examined more critically as additional test data and analyses become available. The program will be revised and updated as required to reflect these additional studies.

CONCLUDING REMARKS

An analyses and computer program for predicting the transient thermal response of a charring ablation thermal protection system has been described. The numerical formulation of the equations is such that an implicit solution is obtained. This method of solution affords both a rapid and accurate solution for both ablating and nonablating type problems.

Provision is made in the program for a number of surface boundary conditions. These provisions allow efficient use of the program for analyzing both ground and flight test data and trajectory synthesis.

The computer program has been checked out with both exact solutions and actual ablation test data. The numerical results are in good agreement with the exact solutions and test data. However, the analysis depends upon using good property values and some effort must be expended in obtaining the best possible thermal properties. The analysis and program will continue to be checked as additional flight and ground test data becomes available, to both update the thermal property values and eliminate the individual approximations and assumptions used in the analysis when possible.

REFERENCES

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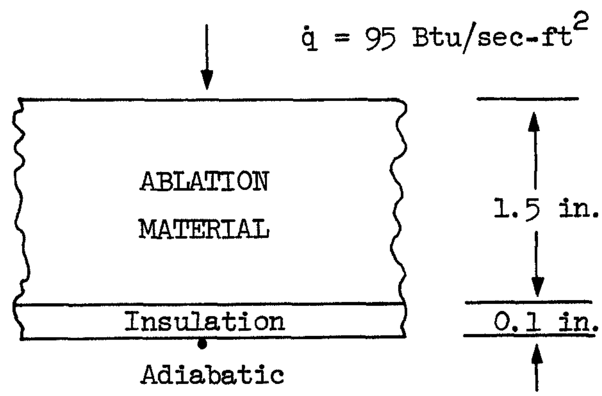
APPENDIX A

SAMPLE PROBLEM

The following sample problem is shown to indicate the form of the data input and the program output. A typical charring material subjected to a constant heating experienced in arc tunnel is presented. A sketch of the model is given below:



The various material properties and dimensions are shown in table II, program output. The insulation is assumed to be ablation material for this problem. The problem coding sheet and subsequent data card listing are shown in table I. The initial temperature of the structure was assumed uniform and equal to 530° R (70° F). Figures 8, 9, and 10 are the output data obtained from the plot routines.

APPENDIX B

PROGRAM IN FORTRAN STATEMENTS

```
$IBFTC MAIN
C
C      STRUCTURES AND MECHANICS DIVISION
C      THERMO-STRUCTURES BRANCH
C      THERMAL PROTECTION SYSTEMS SECTION
C
C      THIS PROGRAM DETERMINES THE PERFORMANCE OF A CHARRING ABLATOR
C
C      ANALYSIS AND PROGRAM DEVELOPED BY DONALD M. CURRY  *  ES32
C
      DIMENSION ESAVE1(3),ESAVE2(3),ESAVE3(3)
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),FMBB(12),HXX(12)
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IFM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
      DIMENSION TIMEP(300),PRES(300),XC(50),TX2C(50),XV(50),XDV(50)
      DIMENSION TS(50),SR(50)
      DIMENSION TTABLE(20),DELTT(20),IPRC(20)
      DIMENSION ASAVE1(3),ASAVE2(3),ASAVE3(3),BSAVE1(3),BSAVE2(3),
     1BSAVE3(3),CSAVE1(3),CSAVE2(3),CSAVE3(3),HEAD(12),
     1DSAVE1(3),DSAVE2(3),DSAVE3(3)
      DIMENSION XRA(30),YA(30)
C
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,FMBB,
     1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
 3000 FORMAT(12A6)
 3001 FORMAT(1X,12A6)
 3002 FORMAT(6E12.8)
 3003 FORMAT(6I5)
 3004 FORMAT(1I5)
 3005 FORMAT(2I5)
 3007 FORMAT(2I5,1E14.8)
 3008 FORMAT(///1X,12A6)
 3009 FORMAT(1H1,1X,12A6)
 3010 FORMAT(4E12.8)
 3011 FORMAT(2E12.8,I6,I5,E13.8,E12.8)
 3012 FORMAT(2E12.8,I6)
      DATA PRVOUS/0545454545454/
      REWIND 11
      STOP=9999.
      READ(5,3003)NCASE
      LPLOT=0
      JCNT=0
```

```
   50 NK=1
      I1=2
      I2=2
      I3=2
      I4=2
      I5=2
      I6=2
      I17=2
      INT=1
      XLOST=0.0
      XMT=0.0
      XMDT=0.0
      ERR1=0.0
      ERR2=0.0
      ERR3=0.0
      ERR4=0.0
      ICT=0
      ICONT=0
      XMDC=0.0
      NKP=1
      XLSTV=0.0
      NRS=2
      ERR5=0.0
      IPCT=0
      ICTP=0
      IPLOT=1
      NXA=1
      NXB=1
      NXC=1
      NXD=1
      SAVY3=-100.
      SAVY4X=-100.
      SX0=0.0
      SDOT=0.0
C
C     GENERAL TITLE OF PROBLEM
  100 READ(5,3000) (HEAD(K),K=1,12)
      WRITE(6,3009) (HEAD(K),K=1,12)
      LPLOT=LPLOT+1
      WRITE (11)(HEAD(I),I=1,12)
      WRITE(6,110)
  110 FORMAT(//1X,11HINPUT DATA.//)
      READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 150
      READ(5,3011)TLIM,TINT,NPTT,NPLOT,DMP,TDMP
      READ(5,3012) (TTABLE(I),DELTT(I),IPRC(I),I=1,NPTT)
      T=TINT
      DTS=DELTT(1)
      DT=DELTT(1)/3600.0
      WRITE(6,120) TLIM,TINT,NPTT
  120 FORMAT(1H0,11HTIME LIMIT=,1PE10.4,4X,13HINITIAL TIME=,1PE10.4,4X,5
     1HNPTT=,I4)
      WRITE(6,122)
  122 FORMAT(//8X,4HTIME,10X,9HTIME STEP,6X,13HPRINT CONTROL)
      WRITE(6,124) (TTABLE(I),DELTT(I),IPRC(I),I=1,NPTT)
  124 FORMAT(5X,1PE10.4,6X,1PE10.4,9X,I4)
C
```

```
C     LOCATION FACTORS FOR CONVECTIVE AND RADIATIVE HEATING
  150 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 200
      READ(5,3002) FCONV,FRAD
      WRITE(6,155) FCONV,FRAD
  155 FORMAT(1H0,6HFCONV=,1PE12.5,4X5HFRAD=,1PE12.5/)
C
C     PROPERTIES OF ABLATION MATERIAL
  200 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 300
      READ(5,3000) (HEADNG(K),K=1,12)
      READ(5,3002) TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,FMC,H300,VL,HV,
     1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC
      REA (5,3003) NP,NKC,NCPC,NKV,NCPV,NREC
      READ(5,3002) (TKC(K),XKC(K),K=1,NKC)
      READ(5,3002) (TCPC(M),CPC(M),M=1,NCPC)
      READ(5,3002) (TKV(L),XKV(L),L=1,NKV)
      READ(5,3002) (TCPV(N),CPV(N),N=1,NCPV)
      READ(5,3002) (TS(I),SR(I),I=1,NREC)
      WRITE(6,3008) (HEADNG(K),K=1,12)
      WRITE(6,210) TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,FMC,H300,VL,HV,
     1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC
  210 FORMAT(1H0,5HTABL=,1PE12.5,3X,6HTCHAR=,1PE12.5,3X,5HTREC=,1PE12.5,
     13X,5HRHOV=,1PE12.5,3X,5HRHOC=,1PE12.5,21X/1X,6HFBLOW=,1PE12.5,4X,4
     2HFMV=,1PE12.5,4X,4HFMC=,1PE12.5,3X,5HH300=,1PE12.5,5X,3HVL=,1PE12.
     35/4X,3HHV=,1PE12.5,4X,4HVPT=,1PE12.5,5X,3HFV=,1PE12.5,5X,3HTV=,1PE
     112.5,2X,6HCHARK=,1PE12.5/1X,6HCHARC=,1PE12.5,3X,5HABLK=,1PE12.5,3X
     2,5HABLC=,1PE12.5/)
      VLI=VL
      VL=VL/12.0
      VLV=VL
      WRITE(6,220) NP,NKC,NCPC,NKV,NCPV,NREC
  220 FORMAT(2X,3HNP=,1I4,4X,4HNKC=,1I4,4X,5HNCPC=,1I4,4X,4HNKV=,1I4,4X,
     15HNCPV=,1I4,4X,5HNREC=,1I4)
      WRITE(6,221)
  221 FORMAT(/32X,15HVIRGIN MATERIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H
     1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)
      KLLL=MIN0(NKV,NCPV)
      WRITE(6,222) (TKV(L),XKV(L),TCPV(L),CPV(L),L=1,KLLL)
  222 FORMAT(2X,1PE12.5,4X,1PE12.5,18X,1PE12.5 ,3X,1PE12.5)
      IF(NKV-NCPV) 223,227,225
  223 KLLLL=KLLL+1
      WRITE(6,224) (TCPV(L),CPV(L),L=KLLLL,NCPV)
  224 FORMAT(48X,1PE12.5,3X,1PE12.5)
      GO TO 227
  225 KLLLL=KLLL+1
      WRITE(6,226) (TKV(L),XKV(L),L=KLLLL,NKV)
  226 FORMAT(2X,1PE12.5,4X,1PE12.5)
  227 WRITE(6,228)
  228 FORMAT(//33X,14HCHAR  MATERIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H
     1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)
      KLLL=MIN0(NKC,NCPC)
      WRITE(6,222) (TKC(L),XKC(L),TCPC(L),CPC(L),L=1,KLLL)
      IF(NKC-NCPC) 230,235,232
  230 KLLLL=KLLL+1
      WRITE(6,224) (TCPC(L),CPC(L),L=KLLLL,NCPC)
      GO TO 235
```

```
  232 KLLLL=KLLL+1
      WRITE(6,226) (TKC(L),XKC(L),L=KLLLL,NKC)
  235 WRITE(6,240)
  240 FORMAT(//28X,23HSURFACE RECESSION TABLE//25X,11HTEMPERATURE,8X,11H
     1SR - IN/SEC)
      WRITE(6,245) (TS(I),SR(I),I=1,NREC)
  245 FORMAT(24X,1PE12.5,7X,1PE12.5)
C
C     PROPERTIES OF TRAJECTORY
  300 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 400
      READ(5,3000) (HEADNG(L),L=1,12)
      READ(5,3004) NTRAPT
      READ(5,3010) (TIME(K),QCON(K),QRAD(K),VEL(K),K=1,NTRAPT)
      WRITE(6,3008) (HEADNG(L),L=1,12)
      WRITE(6,310) NTRAPT
  310 FORMAT(1H0,27H NO. OF TRAJECTORY POINTS =,1I4)
      WRITE(6,320)
  320 FORMAT(//8X,4HTIME,8X,12HQ CONVECTIVE,4X,11HQ RADIATIVE,7X,8HVELOC
     1ITY)
      WRITE(6,330) (TIME(K),QCON(K),QRAD(K),VEL(K),K=1,NTRAPT)
  330 FORMAT(1P4E16.5)
C
C     PROPERTIES OF BACK-UP STRUCTURE
  400 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 500
      WRITE(6,410)
  410 FORMAT(//10X,31H PROPERTIES OF BACKUP STRUCTURE/)
      READ(5,3007) NMB,NPBS,BL
      READ(5,3002) (XNPM(K),K=1,NMB)
      READ(5,415) (NKPB(I),NCPB(I),I=1,NMB)
  415 FORMAT(10I5)
      DO 420 K=1,NMB
      NPM(K)=XNPM(K)+0.00000002
  420 CONTINUE
      WRITE(6,425) NMB,NPBS,BL
  425 FORMAT(/4X,35HNO. OF MATERIALS IN BACK-UP SHIELD=,1I4/4X,40HTOTAL
     1NUMBER OF NODES IN BACK-UP SHIELD=,1I4/4X,28HTHICKNESS OF BACK-UP
     2SHIELD=,1PE12.5//)
      BL=BL/12.0
      DO 440 I=1,NMB
      LK=NKPB(I)
      LCP=NCPB(I)
      READ(5,3000) ((XIDNT(K,I)),K=1,12)
      READ(5,3002) ((TXK(J,I),XK(J,I)),J=1,LK)
      READ(5,3002) ((TCP(J,I),CPX(J,I)),J=1,LCP)
      WRITE(6,432) (XIDNT(K,I),K=1,12)
  432 FORMAT(//12A6)
      WRITE(6,433)
  433 FORMAT(//20X,7HTHERMAL,38X,8HSPECIFIC/3X,11HTEMPERATURE,4X,12HCOND
     1UCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT)
      KLLL=MIN0(LK,LCP)
      DO 434 N=1,KLLL
      WRITE(6,222) (TXK(N,I),XK(N,I),TCP(N,I),CPX(N,I))
  434 CONTINUE
      IF(LK-LCP) 435,440,437
  435 KLLLL=KLLL+1
```

```
      DO 436 N=KLLLL,LCP
      WRITE(6,224) (TCP(N,I),CPX(N,I))
  436 CONTINUE
      GO TO 440
  437 KLLLL=KLLL+1
      DO 438 N=KLLLL,LK
      WRITE(6,226) (TXK(N,I),XK(N,I))
  438 CONTINUE
  440 CONTINUE
      READ(5,3002) (RHOBX(L),XBM(L),EMFB(L),EMBB(L),L=1,NMB)
      READ(5,3002)    (H(J),GAPX(J),FTEST(J),BTEST(J),J=1,NMB)
      WRITE(6,450)
  450 FORMAT(///55X,10HEMISSIVITY/8X,8HMATERIAL,5X,7HDENSITY,7X,9HTHICKN
     1ESS,7X,5HFRONT,9X,4HBACK,7X,14HNODES/MATERIAL/)
      DO 460 LLJ=1,NMB
      WRITE(6,455) LLJ,RHOBX(LLJ),XBM(LLJ),EMFB(LLJ),EMBB(LLJ),XNPM(LLJ)
  455 FORMAT(11X,I1,8X,1PE10.4,4X,1PE10.4,4X,1PE10.4,4X,1PE10.4,6X,1PE1
     10.4/)
  460 CONTINUE
      WRITE(6,465)
  465 FORMAT(//4X,60HADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP
     1STRUCTURE//11X,8HMATERIAL,5X,16HFILM COEFFICIENT,5X,13HGAP THICKNE
     2SS,8X,5HFTEST,13X,5HBTEST)
      DO 480 J=1,NMB
      WRITE(6,470) J,  H(J),GAPX(J),FTEST(J),BTEST(J)
  470 FORMAT(13X,I3,12X,1PE10.4,9X,1PE10.4,7X,1PE11.4,7X,1PE11.4/)
  480 CONTINUE
C
C     PROPERTIES OF ENVIRONMENT
  500 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 600
      READ(5,3000) (HEADNG(L),L=1,12)
      READ(5,3002) TENV,HENV,FENV,QLOSS
      WRITE(6,3008) (HEADNG(L),L=1,12)
      WRITE(6,520) TENV,HENV,FENV,QLOSS
  520 FORMAT(/4X,12HTEMPERATURE=,1PE12.5,4X,17HFILM COEFFICIENT=,1PE12.5
     1,4X,12HVIEW FACTOR=,1PE12.5,4X,7HQ LOST=,1PE12.5)
C
C     INITIAL TEMPERATURE DISTRIBUTION
  600 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 700
      READ(5,3000) (HEADNG(L),L=1,12)
      NPF=NP+NPBS
      TL=VL+BL
      XNP=NP
      DX=VL/(XNP-1.0)
      DXX=DX
      READ(5,3002) TEST2,TEMPI,TX0
      IF(TEST2) 610,620,620
  610 READ(5,3002) (TEMPI(K),K=1,NPF)
      DO 615 K=1,NPF
      TX1(K)=TEMPI(K)
      TX2(K)=TX1(K)
      TUL1(K)=TX1(K)
      TUL2(K)=TX1(K)
  615 CONTINUE
      L=NP+1
```

```
      DO 619 I=1,NMB
      LN=NPM(I)
      DO 617 J=1,LN
      TX2T(J,I)=TEMDI(L)
      L=L+1
  617 CONTINUE
  619 CONTINUE
      GO TO 625
  620 CALL TEMPD
  625 WRITE(6,3008) (HEADNG(L),L=1,12)
      IF(TEST2) 630,635,640
  630 WRITE(6,632)
  632 FORMAT(4X,52HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS ARBRITARY/
     1)
      WRITE(6,633) (TEMDI(K),K=1,NPF)
  633 FORMAT(1P8E12.5)
      GO TO 645
  635 WRITE(6,637) TEMPI
  637 FORMAT(//4X,64HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM
     1AND EQUAL TO ,1PE10.4/)
      GO TO 645
  640 WRITE(6,641)
  641 FORMAT(4X,54HLINEAR TEMPERATURE DISTRIBUTION ASSUMED IN HEAT SHIEL
     1D/)
      WRITE(6,633) (TEMDI(L),L=1,NPF)
  645 IF(DMP) 700,700,646
  646 WRITE(6,647)
  647 FORMAT(//)
  648 WRITE(6,649) (TX1(L),TX2(L),L=1,NPF)
  649 FORMAT(2X,1PE12.5,4X,1PE12.5)
      WRITE(6,650)
  650 FORMAT(//)
C
C     ENTHALPY AS A FUNCTION OF TEMPERATURE
  700 READ(5,3000) (TITLE(L),L=1,12)
      IF(TITLE(1).EQ.PRVOUS) GO TO 725
      READ(5,3004) NHP
      READ(5,3002) (HX(K),TW(K),K=1,NHP)
  725 DO 728 I=1,NP
      TR(I)=0
      TR1(I)=0
      TR2(I)=0
      TEM(I)=0
      XMDG(I)=0.0
  728 CONTINUE
      WRITE(6,730)
  730 FORMAT(1H1,12HOUTPUT DATA.//)
      XC(1)=0.0
      DO 740 I=2,NP
      XC(I)=XC(I-1)+DX
  740 CONTINUE
  750 IF(T-TIME(NK)) 765,770,760
  760 NK=NK+1
      IF(NK-NTRAPT) 750,750,762
  762 WRITE(6,763) NK
  763 FORMAT(1H0,33H THE VALUE OF NK IS IN ERROR, NK=,1I4)
      GO TO 905
```

```
  765 IF(NK-2) 762,766,766
  766 QCONX=QCON(NK-1)+((QCON(NK)-QCON(NK-1))/(TIME(NK)-TIME(NK-1)))
     1*(T-TIME(NK-1))
      QCONX=FCONV*QCONX
      QRADX=QRAD(NK-1)+((QRAD(NK)-QRAD(NK-1))/(TIME(NK)-TIME(NK-1)))
     1*(T-TIME(NK-1))
      QRADX=FRAD*QRADX
      VELX=VEL(NK-1)+((VEL(NK)-VEL(NK-1))/(TIME(NK)-TIME(NK-1)))
     1*(T-TIME(NK-1))
      GO TO 775
  770 QCONX=FCONV*QCON(NK)
      QRADX=FRAD*QRAD(NK)
      VELX=VEL(NK)
C
C     COMPUTE HEAT BLOCKAGE AT FRONT SURFACE
  775 IF(I17-1) 778,778,776
  776 IF(I17-NHP) 777,777,778
  777 IF(TX2(INT)-TW(I17)) 782,788,780
  778 WRITE(6,779) TX2(INT)
  779 FORMAT(1H0,80H THE RANGE OF THE ENTHALPY-TEMPERATURE CURVE FIT WAS
     1EXCEEDED AT A TEMPERATURE OF,1E10.4)
      GO TO 905
  780 I17=I17+1
      GO TO 776
  782 IF(TX2(INT)-TW(I17-1)) 784,788,786
  784 I17=I17-1
      GO TO 775
  786 HW=HX(I17-1)+((HX(I17)-HX(I17-1))/(TW(I17)-TW(I17-1)))
     1*(TX2(INT)-TW(I17-1))
      GO TO 789
  788 HW=HX(I17)
  789 HTX=H300+((VELX**2)/50056.5)
      QBLOCK=(FBLOW*XMDG(INT)*(HTX-HW))/3600.0
C
C     COMPUTE HEAT IN DUE TO SURFACE COMBUSTION
      XMDO=XMDC
      CALL OXIDAT(XMDO,QOXID)
C
C     COMPUTE Q-HOT WALL
      IF(TDMP.EQ.0.) GO TO 4001
      IF(T.GE.TDMP) DMP=1.0
 4001 Z=(HTX-HW)/(HTX-H300)
      IF(Z-1.0) 790,792,793
  790 IF(Z) 791,791,793
  791 QHW=0.0
      GO TO 1790
  792 QHW=QCONX
      GO TO 1790
  793 QHW=Z*QCONX
 1790 ZZZ=(QHW-QBLOCK)/QHW
      IF(ZZZ-0.2) 1798,1798,1794
 1798 QBLOCK=0.8*QHW
C
C     NET HEAT INTO FRONT SURFACE
 1794 IF(IEM(INT)) 795,795,797
  795 IF(TX2(INT)-TCHAR) 796,796,797
  796 EMX=EMV
```

```
      GO TO 798
  797 IFM(INT)=1
      FMX=EMC
  798 QIN=QRADX+QHW+QOXID-QBLOCK-(4.8333E-13)*FMX*FV*((TX2(INT)**4)-
     1(TV**4))
      IF(DMP) 804,804,800
  800 WRITE(6,801)
  801 FORMAT(///)
      WRITE(6,802) QCONX,QRADX,VELX,HTX,HW,Z,QBLOCK,QHW,QOXID,QIN
  802 FORMAT(1X,6HQCONX=,1PE12.5,2X,6HQRADX=,1PE12.5,2X,5HVELX=,1PE12.5,
     12X,4HHTX=,1PE12.5,2X,3HHW=,1PE12.5/1X,2HZ=,1PE12.5,2X,7HQBLOCK=,1P
     2E12.5,2X,4HQHW=,1PE12.5,2X,6HQOXID=,1PE12.5,2X,4HQIN=,1PE12.5/)
  804 QIN=QIN*3600.0
C
C     CHECK FOR FRONT SURFACE RECESSION (CHAR LAYER REMOVAL)
      CALL RECESS(XMDC,XLOST,TREC,DT,RHOC,TS,SR,TX2(1),NREC,NRS,ERR5,SX0
     1,SDOT,DMP)
      IF(ERR5) 8050,8050,905
 8050 VLV=VLV-XLOST
      XLSTV=XLSTV+XLOST
      XLSTI=XLSTV*12.0
      DXV=VLV/(XNP-1.0)
      XV(1)=0.0
      DO 1780 I=2,NP
      XV(I)=XV(I-1)+DXV
 1780 CONTINUE
      DX=DXV
      IF(ERR4) 806,806,805
  805 GO TO 905
  806 CALL COEFF(NPFT,SDOT)
      IF(DMP) 8069,8069,8061
 8061 WRITE(6,8062)
 8062 FORMAT(/1X,23H COEFFICIENTS FOR SWUFT/)
      DO 8066 I=1,NPFT
      WRITE(6,8064)  A(I),B(I),C(I),D(I),I
 8064 FORMAT(1H0,5HA(I)=,1PE12.5,2X,5HB(I)=,1PE12.5,2X,5HC(I)=,1PE12.5,2
     1X,5HD(I)=,1PE12.5,2X,2HI=,I3)
 8066 CONTINUE
 8069 IF(ERR2) 807,807,805
  807 IF(ERR3) 810,810,808
  808 WRITE(6,809) IKK
  809 FORMAT(1H0,18H THE VALUE OF IKK=,1I4)
      GO TO 905
  810 CALL SWUFT(A,B,C,D,TY,NPFT,DMP)
  827 DO 828 I=1,NP
      TX1(I)=TX2(I)
      TX2(I)=TY(I)
  828 CONTINUE
      CALL DON2(XLOST,XV,TX2,NP,XC,TX2C,XDV,KKV,XLSTV,DXX)
  830 CALL ABLATE
      XMDT=XMDG(INT)+XMDC
      LT=NP+1
      DO 1815 I=1,NMB
      LLT=NPM(I)
      IF(I.EQ.1) GO TO 1812
      IF(GAPX(I-1).EQ.0.) GO TO 1812
      KKT=1
```

```
      GO TO 1813
 1812 KKT=2
 1813 DO 1815 J=KKT,LLT
      TX2T(J,I)=TY(LT)
      LT=LT+1
 1815 CONTINUE
      DO 1819 I=1,NMB
      IF(I.EQ.1) GO TO 1816
      IF(GAPX(I-1).EQ.0.) GO TO 1817
      GO TO 1819
 1816 TX2T(1,1)=TY(NP)
      GO TO 1819
 1817 LX=NPM(I-1)
      TX2T(1,I)=TX2T(LX,I-1)
 1819 CONTINUE
      LM=NP+1
      DO 833 I=1,NMB
      LZ=NPM(I)
      DO 833 J=1,LZ
      TX2(LM)=TX2T(J,I)
      LM=LM+1
  833 CONTINUE
      DO 5834 I=2,NPTT
      IF(T-TTABLE(I)) 5835,5835,5834
 5835 DTS=DELTT(I-1)
      IPRCT=IPRC(I-1)
      DT=DELTT(I-1)/3600.0
      GO TO 5836
 5834 CONTINUE
      DTS=DELTT(NPTT)
      IPRCT=IPRC(NPTT)
      DT=DELTT(NPTT)/3600.0
 5836 ICT=ICT+1
 5838 VLTEM=SAVY3
      CALL ISOTHM(XV,TX2,1060. ,NP,SAVEIT)
      SAVEIT=SAVEIT+XLSTV
      IF(SAVY3.LT.SAVEIT)SAVY3=SAVEIT
      IF(VLTEM.EQ.SAVY3)GO TO 839
      SAVX=T
      SAVY1=XLSTI
      SAVY2=TX2(NP)
      CALL ISOTHM(XV,TX2,1460.,NP,SAVY4)
  839 BLTEM=SAVY4X
      CALL ISOTHM(XV,TX2,1460.,NP,WEKEEP)
      WEKEEP=WEKEEP+XLSTV
      IF(SAVY4X.LT.WEKEEP)SAVY4X=WEKEEP
      IF(BLTEM.EQ.SAVY4X)GO TO 838
      SAVEXX=T
      SAVY1X=XLSTI
      SAVY2X=TX2(NP)
      CALL ISOTHM(XV,TX2,1060.,NP,SAVY3X)
  838 CONTINUE
      IF(IPRCT-ICT) 835,835,840
  835 WRITE(6,837) T,QCONX,QRADX,VELX,XMDG(INT),XMDC,XMDT,XLSTI,QHW
  837 FORMAT(1H0,5HTIME=,
     1                   1PE12.5,2X,12HQCONVECTIVE=,1PE12.5,2X,11HQRADIAT
     1IVE=,1PE12.5,2X,9HVELOCITY=,1PE12.5/1X,18HGAS ABLATION RATE=,1PE12
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```
     2.5,2X,19HCHAR ABLATION RATE=,1PE12.5,2X,20HTOTAL ABLATION RATE=,1P
     3E12.5/1X,16HRECESSION DEPTH=,1PE12.5,2X,10HHOT WALL=,1PE12.5)
  840 T=T+DTS
  841 IF(NPLOT.NE.1) GO TO 842
      CALL SAVE(ASAVE1,ASAVE2,ASAVE3,USEA,NXA,XLSTI,DTS,TLIM,T,VALUEA)
      CALL SAVE(BSAVE1,BSAVE2,BSAVE3,USEB,NXB,TX2(NP),DTS,TLIM,T,VALUEB)
      CALL ISOTHM(XV,TX2,1060.,NP,Y3)
      CALL SAVE(CSAVE1,CSAVE2,CSAVE3,USEC,NXC,Y3,DTS,TLIM,T,VALUEC)
      CALL ISOTHM(XV,TX2,1460.,NP,Y4)
      CALL SAVE(DSAVE1,DSAVE2,DSAVE3,USED,NXD,Y4,DTS,TLIM,T,VALUED)
      IF(USEA.NE.0.0)GO TO 9842
      IF(USEB.NE.0.0)GO TO 9842
      IF(USEC.NE.0.0)GO TO 9842
      IF(USED.NE.0.0)GO TO 9842
      GO TO 9843
 9842 XPLOT=T-DTS
      YPLOT1=VALUEA
      IF(USEA.NE.0.0)YPLOT1=USEA
      YPLOT2=VALUEB
      IF(USEB.NE.0.0)YPLOT2=USEB
      YPLOT3=VALUEC
      IF(USEC.NE.0.0)YPLOT3=USEC
      YPLOT4=VALUED
      IF(USED.NE.0.0)YPLOT4=USED
      WRITE (11)XPLOT,YPLOT1,YPLOT2,YPLOT3,YPLOT4
 9843 IF(ICTP.NE.0) GO TO 842
      ICTP=1
      XPLOT=T
      YPLOT1=XLSTI
      YPLOT2=TX2(NP)
      CALL ISOTHM(XV,TX2,1060.,NP,YPLOT3)
      CALL ISOTHM(XV,TX2,1460.,NP,YPLOT4)
      WRITE (11)XPLOT,YPLOT1,YPLOT2,YPLOT3,YPLOT4
  842 IF(IPRCT-ICT) 845,845,900
  845 WRITE(6,850) T
      IPCT=IPCT+1
      IF(IPCT.EQ.2)IPCT=0
      IF(IPCT.EQ.0)ICTP=0
  850 FORMAT(1H0,72HTEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END O
     1F THE TIME STEP, T= ,1PE12.5,1X,7HSECONDS//)
      WRITE(6,860)
  860 FORMAT(4X,49HTEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL//)
      KKV=KKV+1
      WRITE(6,862) (TX2C(I),I=1,KKV)
  862 FORMAT(6X,1PE12.5,1P5E16.5)
      IJ=NP+1
      WRITE(6,864)
  864 FORMAT(//4X,49HTEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE//
     1)
      WRITE(6,862) (TX2(I),I=IJ,NPE)
      WRITE(6,865)
  865 FORMAT(//)
      ICT=0
  900 CONTINUE
      IF(T-TLIM) 750,750,905
  905 IF(NPLOT.NE.1) GO TO 909
      XAVY3=SAVY3-SAVY1/12.
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```
      XAVY4X=SAVY4X-SAVY1X/12.
      IF(SAVX.EQ.XPLOT)GO TO 9005
      WRITE(11)SAVX,SAVY1,SAVY2,XAVY3,SAVY4
 9005 IF(SAVEXX.EQ.XPLOT)GO TO 9006
      SAV4I=SAVY4X*12.
 9006 SAV3I=SAVY3*12.
      WRITE(11)SAVEXX,SAVY1X,SAVY2X,SAVY3X,XAVY4X
      WRITE(6,929)SAV3I,SAV4I
  929 FORMAT(1H0,23HMAXIMUM 1060 ISOTHERM =E16.8,2X23HMAXIMUM 1460 ISOTH
     1ERM =E16.8)
      WRITE (11)STOP,STOP,STOP,STOP,STOP
  909 IF(LPLOT.NE.NCASE)GO TO 911
      DATA END/6H   END /
      WRITE(11)END,END,END,END,END,END,END,END,END,END,END,END
      QUIT=8888.
      WRITE(11)QUIT,QUIT,QUIT,QUIT,QUIT
      END FILE 11
      REWIND 11
  911 IF(TEST2) 910,930,930
  910 DO 920 JJK=1,NPF
      TX1(JJK)=TEMPT(JJK)
      TX2(JJK)=TX1(JJK)
      TUL1(K)=TX1(K)
      TUL2(K)=TX1(K)
  920 CONTINUE
      IL=NP+1
      DO 926 I=1,NMB
      ILN=NPM(1)
      DO 924 J=1,ILN
      TX2T(J,I)=TEMPI(IL)
      IL=IL+1
  924 CONTINUE
  926 CONTINUE
      GO TO 940
  930 CALL TEMPD
  940 T=TINT
      DX=DXX
      DTS=DELTT(1)
      DT=DELTT(1)/3600.0
      VLV=VL
      GO TO 50
      END
```

```
$IBFTC COEF
C     THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF THE MATRIX
      SUBROUTINE COEFF(NPET,SDOT)
C
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBB(12),HXX(12)
     4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,FMBB,
     1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
      CALL PROP
      YNP=NP
      S(INT)=(RHO(INT)*DX*CP(INT))/(2.0*DT)
      R(INT)=(1.0)/((DX/2.0)*((1.0/YK(INT))+(1.0/YK(INT+1))))
      A(INT)=0.0
      B(INT)=(-((XMDG(INT)+XMDC)*CP(INT)+S(INT)+R(INT)-RHO(INT)*CP(INT)
     1*(SDOT/(2.0*(YNP-1.0)))))
      C(INT)=XMDG(INT+1)*CP(INT+1)+R(INT)+RHO(INT+1)*CP(INT+1)*SDOT
     1*(YNP-1.5/(YNP-1.0))
      D(INT)=(-(QIN+S(INT)*TX2(INT))) +(XMDG(INT)-XMDG(INT+1))*HV
      NPP=NP-1
      JNT=INT+1
      DO 10 I=JNT,NPP
      XI=I
      S(I)=(RHO(I)*DX*CP(I))/DT
      R(I)=(1.0)/((DX/(2.0*YK(I)))+(DX/(2.0*YK(I+1))))
      A(I)=R(I-1)
      B(I)=(-(XMDG(I)*CP(I)+R(I-1)+R(I)+S(I)+ RHO(I)*CP(I)*SDOT*((YNP-XI
     1-0.5)/(YNP-1.0))))
      C(I)=XMDG(I+1)*CP(I+1)+R(I)+RHO(I+1)*CP(I+1)*SDOT*((YNP-XI-0.5)
     1/(YNP-1.0))
      D(I)=(-(S(I)*TX2(I))) +(XMDG(I)-XMDG(I+1))*HV
   10 CONTINUE
      R(NP)=(1.0)/((DXB(1)    /(2.0*XKB(1,1)))+(DXB(1)   /(2.0*XKB(2,1))))
      S(NP)=(RHO(NP)*DX*CP(NP)+RHOBX(1)* CPB(1,1)*DXB(1))/(2.0*DT)
      A(NP)=R(NP-1)
      B(NP)=(-(XMDG(NP)*CP(NP)+R(NP-1)+R(NP)+S(NP)))
      C(NP)=R(NP)
      D(NP)=(-S(NP)*TX2(NP)) +XMDG(NP)*HV
      DO 200 I=1,NMB
      IF(I-1) 20,20,30
   20 AB(1,I)=A(NP)
```

```
      BB(1,I)=B(NP)
      CB(1,I)=C(NP)
      DB(1,I)=D(NP)
      GO TO 65
   30 L=NPM(I-1)
      IF(FTEST(I)) 45,40,45
   40 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I)+RHOBX(I-1)*CPB(L,I-1)*DXB(I-1))/
     1(2.0*DT)
      RB1(1,I)=(1.0)/((DXB(I-1)/(2.0*XKB(L,I-1)))+(DXB(I-1)/(2.0*XKB(L-1
     1,I-1))))
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I))))
      AB(1,I)=RB1(1,I)
      BB(1,I)=(-(RB1(1,I)+RB2(1,I)+SB(1,I)))
      CB(1,I)=RB2(1,I)
      DB(1,I)=(-(SB(1,I)*TX2T(1,I)))
      GO TO 65
   45 IF(FTEST(I)) 50,40,55
   50 G=(1.73E-09)/(1.0/EMBB(I-1)+1.0/EMFB(I)-1.0)
      GO TO 60
   55 G=0.0
   60 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I))/(2.0*DT)
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I))))
      AB(1,I)=H(I-1)+4.0*G*(TX2T(L,I-1)**3)
      BB(1,I)=(-(H(I-1)+4.0*G*(TX2T(1,I   )**3)+RB2(1,I)+SB(1,I)))
      CB(1,I)=RB2(1,I)
      DB(1,I)=3.0*G*((TX2T(L,I-1)**4)-(TX2T(1,I)**4))-SB(1,I)*TX2T(1,I)
   65 LF=NPM(I)-1
      DO 100 J=2,LF
      SB(J,I)=(RHOBX(I)*CPB(J,I)*DXB(I))/DT
      RB1(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J-1,I)))+(DXB(I)/(2.0*XKB(J,I))))
      RB2(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J+1,I)))+(DXB(I)/(2.0*XKB(J,I))))
      AB(J,I)=RB1(J,I)
      BB(J,I)=(-(RB1(J,I)+RB2(J,I)+SB(J,I)))
      CB(J,I)=RB2(J,I)
      DB(J,I)=(-(SB(J,I)*TX2T(J,I)))
  100 CONTINUE
      IF(I-NMB) 110,250,250
  110 LNF=NPM(I)
      IF(BTEST(I)) 120,115,120
  115 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I)+RHOBX(I+1)*CPB(1,I+1)*DXB(I+
     11))/(2.0*DT)
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF
     1,I))))
      RB2(LNF,I)=(1.0)/((DXB(I+1)/(2.0*XKB(1,I+1)))+(DXB(I+1)/
     1(2.0*XKB(2,I+1))))
      AB(LNF,I)=RB1(LNF,I)
      BB(LNF,I)=(-(RB1(LNF,I)+RB2(LNF,I)+SB(LNF,I)))
      CB(LNF,I)=RB2(LNF,I)
      DB(LNF,I)=(-(SB(LNF,I)*TX2T(LNF,I)))
      GO TO 200
  120 IF(BTEST(I)) 125,115,127
  125 G=(1.73E-09)/(1.0/EMBB(I)+1.0/EMFB(I+1)-1.0)
      GO TO 130
  127 G=0.0
  130 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I))/(2.0*DT)
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF
     1,I))))
```

```
      AB(LNF,I)=RB1(LNF,I)
      BB(LNF,I)=(-(RB1(LNF,I)+H(I)+SB(LNF,I)+4.0*G*(TX2T(LNF,I)**3)))
      CB(LNF,I)=H(I)+4.0*G*(TX2T(1,I+1)**3)
      DB(LNF,I)=3.0*G*((TX2T(1,I+1)**4)-(TX2T(LNF,I)**4))-SB(LNF,I)*TX2T
     1(LNF,I)
  200 CONTINUE
  250 MN=NPM(NMB)
      IF(QLOSS) 270,260,270
  260 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)
      RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*XK
     1B(MN,NMB))))
      AB(MN,NMB)=RB1(MN,NMB)
      BB(MN,NMB)=(-(RB1(MN,NMB)+SB(MN,NMB)))
      CB(MN,NMB)=0.0
      DB(MN,NMB)=(-(SB(MN,NMB)*TX2T(MN,NMB)))
      GO TO 280
  270 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT)
      RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.0*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*X
     1KB(MN,NMB))))
      AB(MN,NMB)=RB1(MN,NMB)
      BB(MN,NMB)=(-(RB1(MN,NMB)+HENV+(1.73E-09)*EENV*4.0*(TX2T(MN,NMB)**
     13)+SB(MN,NMB)))
      CB(MN,NMB)=0.0
      DB(MN,NMB)=(-(HENV*TENV+EENV*(1.73E-09)*((TENV**4)+3.0*(TX2T(MN,NM
     1B)**4))+SB(MN,NMB)*TX2T(MN,NMB)))
  280 L=NP+1
      DO 300 I=1,NMB
      K=NPM(I)
      IF(I.EQ.1) GO TO 282
      IF(GAPX(I-1).EQ.0.) GO TO 282
      KT=1
      GO TO 285
  282 KT=2
  285 DO 290 J=KT,K
      A(L)=AB(J,I)
      B(L)=BB(J,I)
      C(L)=CB(J,I)
      D(L)=DB(J,I)
      IF(DMP) 289,289,286
  286 WRITE(6,287) AB(J,I),BB(J,I),CB(J,I),DB(J,I),J,I,A(L),B(L),C(L),D(
     1L),L
  287 FORMAT(1H0,8HAB(J,I)=,1PE12.5,2X,8HBB(J,I)=,1PE12.5,2X,8HCB(J,I)=,
     11PE12.5,2X,8HDB(J,I)=,1PE12.5,2X,2HJ=,I3,2X,2HI=,I3/1X,5HA(L)=,1PE
     212.5,2X,5HB(L)=,1PE12.5,2X,5HC(L)=,1PE12.5,2X,5HD(L)=,1PE12.5,2X,2
     3HL=,I3)
  289 L=L+1
  290 CONTINUE
  300 CONTINUE
      NPET=L-1
      RETURN
      END
```

```
$IBFTC PRP
C     THIS SUBROUTINE DETERMINES THE PHYSICAL PROPERTIES OF THE
C        HEAT SHIELD STRUCTURE
      SUBROUTINE PROP
C
      DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
     1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
     2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
     3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBB(12),HXX(12)
     4,GAPX(12),FTEST(12),RTEST(12),TEMDI(200),TX1(200),TX2(200),
     5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
     6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
     7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
     8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
     9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
      DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,FMBB,
     1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,RTEST,TEMDI,TX1,
     2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
     3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
     4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
     5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
     1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
      KINT=INT
      DO 170 I=KINT,NP
   10 IF(IR(I)) 12,12,100
   12 TUL(I)=AMAX1(TX1(I),TX2(I))
      IF(TUL(I).LE.TABL) GO TO 20
      IR(I)=1
      GO TO 100
   20 IF(I1-1) 25,25,21
   21 IF(I1-NKV) 22,22,25
   22 IF(TX2(I)-TKV(I1)) 35,55,30
   25 WRITE(6,26) TX2(I)
   26 FORMAT(1H0,87H THE RANGE OF ONE OF THE ABLATION PROPERTY CURVE FIT
     1S WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5)
      ERR2=1.0
      GO TO 355
   30 I1=I1+1
      GO TO 21
   35 IF(TX2(I)-TKV(I1-1)) 40,55,50
   40 I1=I1-1
      GO TO 20
   50 YK(I)=XKV(I1-1)+((XKV(I1)-XKV(I1-1))/(TKV(I1)-TKV(I1-1)))
     1*(TX2(I)-TKV(I1-1))
      GO TO 60
   55 YK(I)=XKV(I1)
   60 IF(I2-1) 25,25,61
   61 IF(I2-NCPV) 62,62,25
   62 IF(TX2(I)-TCPV(I2)) 70,85,65
   65 I2=I2+1
      GO TO 61
   70 IF(TX2(I)-TCPV(I2-1)) 75,85,80
   75 I2=I2-1
```

```
      GO TO 60                                                          C0570
   80 CP(I)=CPV(I2-1)+((CPV(I2)-CPV(I2-1))/(TCPV(I2)-TCPV(I2-1)))      C0580
     1*(TX2(I)-TCPV(I2-1))                                              C0590
      GO TO 90                                                          C0600
   85 CP(I)=CPV(I2)                                                     C0610
   90 RHO(I)=RHOV                                                       C0620
      GO TO 170                                                         C0630
  100 TUL(I)=AMAX1(TUL(I),TX2(I))                                       C0640
      IF(TUL(I)-TCHAR) 110,110,115                                      C0650
  110 RHO(I)=RHOV+(RHOV-RHOC)*((TUL(I)-TABL)/(TABL-TCHAR))              C0660
      YK(I)=CHARK+(ABLK-CHARK)*((RHO(I)-RHOC)/(RHOV-RHOC))              C0670
      CP(I)=CHARC+(ABLC-CHARC)*((RHO(I)-RHOC)/(RHOV-RHOC))              C0680
      GO TO 170                                                         C0690
  115 IF(VPT) 116,116,117                                               C0700
  116 TTUL(I)=TUL(I)                                                    C0710
      GO TO 120                                                         C0720
  117 TTUL(I)=TX2(I)                                                    C0730
  120 IF(I3-1) 25,25,121                                                C0740
  121 IF(I3-NKC) 122,122,25                                             C0750
  122 IF(TTUL(I)-TKC(I3)) 124,135,123                                   C0760
  123 I3=I3+1                                                           C0770
      GO TO 121                                                         C0780
  124 IF(TTUL(I)-TKC(I3-1)) 125,135,130                                 C0790
  125 I3=I3-1                                                           C0800
      GO TO 120                                                         C0810
  130 YK(I)=XKC(I3-1)+((XKC(I3)-XKC(I3-1))/(TKC(I3)-TKC(I3-1)))         C0820
     1*(TTUL(I)-TKC(I3-1))                                              C0830
      GO TO 140                                                         C0840
  135 YK(I)=XKC(I3)                                                     C0850
  140 IF(I4-1) 25,25,141                                                C0860
  141 IF(I4-NCPC) 142,142,25                                            C0870
  142 IF(TTUL(I)-TCPC(I4)) 150,165,145                                  C0880
  145 I4=I4+1                                                           C0890
      GO TO 141                                                         C0900
  150 IF(TTUL(I)-TCPC(I4-1)) 155,165,160                                C0910
  155 I4=I4-1                                                           C0920
      GO TO 140                                                         C0930
  160 CP(I)=CPC(I4-1)+((CPC(I4)-CPC(I4-1))/(TCPC(I4)-TCPC(I4-1)))      C0940
     1*(TTUL(I)-TCPC(I4-1))                                             C0950
      GO TO 166                                                         C0960
  165 CP(I)=CPC(I4)                                                     C0970
  166 RHO(I)=RHOC                                                       C0980
  170 CONTINUE                                                          C0990
C                                                                       C1000
C     DETERMINATION OF PROPER BACK-UP SHIELD MATERIAL PROPERTY          C1010
C                                                                       C1020
      DO 300 I=1,NMB                                                    C1030
      DXB(I)=XBM(I)/((XNPM(I)-1.0)*12.0)                                C1040
      LKP=NKPB(I)                                                       C1050
      LCP=NCPB(I)                                                       C1060
      NN=NPM(I)                                                         C1070
      DO 280 J=1,NN                                                     C1080
  200 IF(I5-1) 203,203,201                                              C1090
  201 IF(I5-LKP) 202,202,203                                            C1100
  202 IF(TX2T(J,I)-TXK(I5,I)) 206,220,205                               C1110
  203 WRITE(6,204) I,TX2T(J,I)                                          C1120
  204 FORMAT(1H0,32H THE RANGE OF ONE OF THE NUMBER ,I2,71H BACKUP STRUC  C1130
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```
     1TURE PROPERTY CURVE FITS WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5
     2)
      ERR2=1.0
      GO TO 355
  205 I5=I5+1
      GO TO 201
  206 IF(TX2T(J,I)-TXK(I5-1,I)) 210,220,215
  210 I5=I5-1
      GO TO 200
  215 XKB(J,I)=XK(I5-1,I)+((XK(I5,I)-XK(I5-1,I))/(TXK(I5,I)-TXK(I5-1,I))
     1)*(TX2T(J,I)-TXK(I5-1,I))
      GO TO 230
  220 XKB(J,I)=XK(I5,I)
  230 IF(I6-1) 203,203,231
  231 IF(I6-LCP) 232,232,203
  232 IF(TX2T(J,I)-TCP(I6,I)) 234,245,233
  233 I6=I6+1
      GO TO 231
  234 IF(TX2T(J,I)-TCP(I6-1,I)) 235,245,240
  235 I6=I6-1
      GO TO 230
  240 CPB(J,I)=CPX(I6-1,I)+((CPX(I6,I)-CPX(I6-1,I))/(TCP(I6,I)-TCP(I6-1,
     1I)))*(TX2T(J,I)-TCP(I6-1,I))
      GO TO 280
  245 CPB(J,I)=CPX(I6,I)
  280 CONTINUE
      I5=2
      I6=2
  300 CONTINUE
  310 IF(DMP) 355,355,320
  320 WRITE(6,330)
  330 FORMAT(/1X,32H PROPERTIES OF ABLATION MATERIAL/)
      WRITE(6,335)
  335 FORMAT(/5X,5HYK(I),9X,5HCP(I),9X,6HRHO(I)/)
      WRITE(6,340) (YK(I),CP(I),RHO(I),I=1,NP)
  340 FORMAT(2X,1PE12.5,2X,1PE12.5,2X,1PE12.5)
      WRITE(6,345)
  345 FORMAT(//1X,32H PROPERTIES OF BACK-UP STRUCTURE/)
      WRITE(6,347)
  347 FORMAT(/5X,8HYKB(J,I),7X,8HCPB(J,I),7X,8HRHOBX(I),7X,7HEMEB(I),8X,
     17HEMBB(I),9X,6HDXB(I)/)
      DO 350 I=1,NMB
      KL=NPM(I)
      DO 349 J=1,KL
      WRITE(6,348) YKB(J,I),CPB(J,I),RHOBX(I),EMEB(I),EMBB(I),DXB(I)
  348 FORMAT(3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1PE12.5,3X,1
     1PE12.5)
  349 CONTINUE
  350 CONTINUE
  355 RETURN
      END
```

```
$IBFTC ABL
C      THIS SUBROUTINE DETERMINES THE MASS FLOW RATE FROM THE
C        ABLATING NODES
       SUBROUTINE ABLATE
C
       DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
      1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
      2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
      3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMEB(12),EMBR(12),HXX(12)
      4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
      5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
      6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
      7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
      8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
      9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
       DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
       COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBR,
      1EMEB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
      2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
      3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
      4TABL,TCHAR,TREF,RHOV,RHOC,FBLOW,EMV,EMC,H300,NKC,NCPC,NKV,NCPV,
      5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,EENV,QLOSS,TLIM,TINT
       COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
      1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDG,H
C
       XMT=0.0
       LINT=INT
       KI=NP
       IF(DMP) 8,8,3
     3 WRITE(6,5)
     5 FORMAT(//1X,29HMASS FLOW FROM ABLATING NODES//)
     8 DO 200 KKI=LINT,NP
       IF(IR1(KI)) 11,11,12
    11 IF(TX1(KI).LE.TABL) GO TO 9
    12 TUL1(KI)=AMAX1(TUL1(KI),TX1(KI))
       IR1(KI)=1
       GO TO 20
     9 IF(TX1(KI)-TABL) 10,10,20
    10 RHOY1(KI)=RHOV
       GO TO 50
    20 IF(TUL1(KI)-TCHAR) 40,30,30
    30 RHOY1(KI)=RHOC
       GO TO 50
    40 RHOY1(KI)=RHOV+(RHOV-RHOC)*((TUL1(KI)-TABL)/(TABL-TCHAR))
    50 IF(IR2(KI)) 52,52,54
    52 IF(TX2(KI).LE.TABL) GO TO 56
    54 TUL2(KI)=AMAX1(TUL2(KI),TX2(KI))
       IR2(KI)=1
       GO TO 70
    56 IF(TX2(KI)-TABL) 60,60,70
    60 RHOY2(KI)=RHOV
       GO TO 95
    70 IF(TUL2(KI)-TCHAR) 90,80,80
    80 RHOY2(KI)=RHOC
       GO TO 95
    90 RHOY2(KI)=RHOV+(RHOV-RHOC)*((TUL2(KI)-TABL)/(TABL-TCHAR))
```

```
 95 DRHO(KI)=((RHOY1(KI)-RHOY2(KI))/DT)*DX
    IF(KI-NP) 97,96,96
 96 DRHO(KI)=DRHO(KI)/2.0
    GO TO 98
 97 IF(KI-INI) 96,96,98
 98 IF(DRHO(KI)) 110,120,120
110 DRHO(KI)=0.0
120 XMT=XMT+DRHO(KI)
    XMDG(KI)=XMT
    IF(DMP) 190,190,150
150 WRITE(6,160) XMDG(KI),DRHO(KI),RHOY2(KI),RHOY1(KI)
160 FORMAT(1X,5HXMDG=,1PE12.5,2X,5HDRHO=,1PE12.5,2X,6HRHOY2=,1PE12.5,2
   1X,6HRHOY1=,1PE12.5)
190 KI=KI-1
200 CONTINUE
    RETURN
    END
```

```
$IBFTC OXID                                                                   F0000
C                                                                             F0010
C     THIS SUBROUTINE CALCULATES THE HEATING RATE DUE TO COMBUSTION          F0020
C     IT IS ASSUMED THAT OXYGEN AND CARBON REACT  TO FORM CO ONLY.           F0030
C                                                                             F0040
      SUBROUTINE OXIDAT(XMDO,QOXID)                                           F0050
C                                                                             F0060
      QOXID=XMDO*4000.0/3600.0                                                F0070
      QOXID=0.0                                                               F0080
      RETURN                                                                  F0090
      END                                                                     F0100
```

```
$IBFTC SWUFT
C      THIS SUBROUTINE DETERMINES THE FORWARD TIME STEP TEMPERATURES
C      BY SOLVING THE TRI-DIAGONAL MATRIX
       SUBROUTINE SWUFT(A,B,C,D,T,N,DMP)
       DIMENSION A(200),B(200),C(200),D(200),T(200),CP(200),DP(200)
       CP(1)=C(1)/B(1)
       DP(1)=D(1)/B(1)
       DO 100 I=2,N
       CP(I)=C(I)/(B(I)-A(I)*CP(I-1))
       DP(I)=(D(I)-A(I)*DP(I-1))/(B(I)-A(I)*CP(I-1))
  100  CONTINUE
       T(N)=DP(N)
       NM1=N-1
       DO 200 J=1,NM1
       I=N-J
       T(I)=DP(I)-CP(I)*T(I+1)
  200  CONTINUE
       IF(DMP) 300,300,250
  250  WRITE(6,260)
  260  FORMAT(//1X,43HCOEFFICIENTS CALCULATED BY SUBROUTINE SWUFT//)
       WRITE(6,270)
  270  FORMAT(6X,5HCP(I),10X,5HDP(I),10X,4HT(I)/)
       WRITE(6,275) (CP(I),DP(I),T(I),I=1,N)
  275  FORMAT(2X,1PE12.5,2X,1PE12.5,2X,1PE12.5)
  300  RETURN
       END
```

```
$IBFTC REC
C
C     THIS SUBROUTINE DETERMINES THE FRONT FACE LOCATION AND CHAR MASS
C     REMOVAL RATE
C
      SUBROUTINE RECESS(XMDC,XLOST,TREC,DT,RHOC,TS,SR,TX2,NREC,NRS,ERR5,
     1SX0,SDOT,DMP)
C
      DIMENSION TS(50),SR(50)
      IF(TX2-TREC) 10,20,20
   10 XMDC=0.0
      XLOST=0.0
      SDOT=0.0
      GO TO 60
   20 IF(NRS-1)25,25,21
   21 IF(NRS-NREC) 22,22,25
   22 IF(TX2-TS(NRS)) 32,40,30
   25 WRITE(6,26) TX2
   26 FORMAT(1H0,75H THE RANGE OF THE SURFACE RECESSION TABLE WAS EXCEED
     1ED AT A TEMPERATURE OF ,1PE12.5)
      ERR5=1.0
      GO TO 60
   30 NRS=NRS+1
      GO TO 21
   32 IF(TX2-TS(NRS-1)) 34,40,36
   34 NRS=NRS-1
      GO TO 20
   36 SX=SR(NRS-1)+((SR(NRS)-SR(NRS-1))/(TS(NRS)-TS(NRS-1)))
     1*(TX2-TS(NRS-1))
      GO TO 50
   40 SX=SR(NRS)
   50 XLOST=300.0*SX*DT
      XMDC=(XLOST*RHOC)/DT
      SDOT=SX*300.0
      IF(DMP) 60,60,52
   52 WRITE(6,54) SX,XLOST,XMDC
   54 FORMAT(1H0,3HSX=,1PE12.5,3X,6HXLOST=,1PE12.5,3X,5HXMDC=,1PE12.5)
   60 RETURN
      END
```

```
$IBFTC TEMP
C       THIS SUBROUTINE DETERMINES THE INITIAL TEMPERATURE DISTRIBUTION
C       IN THE HEAT SHIELD STRUCTURE
        SUBROUTINE TEMPD
C
        DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),
       1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
       2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)
       3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBB(12),HXX(12)
       4,GAPX(12),FTEST(12),BTEST(12),TEMDI(200),TX1(200),TX2(200),
       5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
       6IR2(50),TUL(50),IFM(50),TY(200),A(200),B(200),C(200),D(200),
       7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),
       8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),
       9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)
        DIMENSION TTUL(50),RHOY1(50),RHOY2(50),DRHO(50),TCPC(20)
C
        COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,FMBB,
       1FMFB,NKPB,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,
       2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,
       3RB1,RB2,TY,RHOY1,RHOY2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,
       4TABL,TCHAR,TREC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
       5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT
        COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,
       1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H
C
        X=0.0
        IF(TEST2) 300,100,200
  100   DO 150 L=1,NPF
        TX1(L)=TEMPI
        TX2(L)=TEMPI
        TUL1(L)=TX1(L)
        TUL2(L)=TX2(L)
        TEMDI(L)=TEMPI
  150   CONTINUE
        DO 160 I=1,NMB
        JN=NPM(I)
        DO 155 M=1,JN
        TX2T(M,I)=TEMPI
  155   CONTINUE
  160   CONTINUE
        GO TO 320
  200   DO 220 L=1,NP
        TEMDI(L)=TX0+((TENV-TX0)/TL)**X
        TX1(L)=TEMDI(L)
        TX2(L)=TX1(L)
        TUL1(L)=TX1(L)
        TUL2(L)=TX1(L)
        X=X+DX
  220   CONTINUE
        L=NP+1
        DO 270 I=1,NMB
        KJ=NPM(I)
        DO 250 J=1,KJ
        TEMDI(L)=TX0+((TENV-TX0)/TL)**X
        TX1(L)=TEMDI(L)
        TX2(L)=TEMDI(L)
```

```
      TX2T(J,I)=TEMPI(L)
      X=X+DXB(I)
      L=L+1
  250 CONTINUE
      X=X+(GAPX(I)/12.0)
  270 CONTINUE
      GO TO 320
C     AN ARBRITARY TEMPERATURE DISTRIBUTION CAN BE READ IN FROM INPUT
C      DATA IF TEST2 IS A NEGATIVE NUMBER
  300 WRITE(6,310)
  310 FORMAT(1H0,79H THE VALUE OF TEST2 WAS NEGATIVE, SUBROUTINE TEMPD S
     1HOULD NOT HAVE BEEN CALLED.)
      ERR1=1.0
  320 RETURN
      END
```

```
$IBFTC DON2
C     THIS SUBROUTINE DETERMINES THE TEMPERATURE OF POINTS A FIXED
C     DISTANCE FROM A REFERENCE PLANE FROM THE TEMPERATURES CALCULATED
C     IN A VARYING THICKNESS
C
      SUBROUTINE DON2(XLOST,XARRAY,TARRAY,NA,XNODE,TEMP,XNODEV,KK,XLSTV,
     1DX)
C
      DIMENSION XARRAY(50),TARRAY(50),XNODE(50),TEMP(50),XNODEV(50)
C
      K=0
      DXT=0.0
      DO 100 I=1,NA
      IF(XLSTV.LE.DXT) GO TO 150
      K=K+1
  100 DXT=DXT+DX
  150 KK=NA-K
      XK=K
      XNODEV(1)=XLSTV
      TEMP(1)=TARRAY(1)
      DO 200 I=1,KK
      XNODE(I)=XK*DX-XLSTV
      CALL DISCT3(XNODE(I),XARRAY,TARRAY,NA,TEMP(I+1) )
      XNODEV(I+1)=XK*DX
  200 XK=XK+1.0
      RETURN
      END
```

```
$IBFTC UINTRP
      SUBROUTINE UINTRP(X,XTBL,Y,YTBL,N,J)
      DIMENSION XTBL(50),YTBL(50)
      I=J
      IF(I.GT.N.OR.I.LT.2) I=2
   10 IF(XTBL(I-1).LE.X.AND.X.LE.XTBL(I)) GO TO 40
      IF(X.GT.XTBL(I)) GO TO 30
   20 I=I-1
      IF(I.GE.2) GO TO 10
      I=2
      GO TO 40
   30 I=I+1
      IF(I.LE.N) GO TO 10
      I=N
   40 FRACT=(X-XTBL(I-1))/(XTBL(I)-XTBL(I-1))
      Y=YTBL(I-1)+(YTBL(I)-YTBL(I-1))*FRACT
      RETURN
      END
```

```
$IBFTC ISOT
      SUBROUTINE ISOTHM(DEPTH,TEMP,BOND,N,ANS)
      DIMENSION DEPTH(1),TEMP(1)
      ANS=-1.
      K=N-1
      DO 100 I=1,K
      IF(TEMP(I)-BOND)2,1,3
    1 ANS=DEPTH(I)
      GO TO 100
    2 IF(TEMP(I+1)-BOND)100,100,4
    4 ANS=DEPTH(I+1)-(TEMP(I+1)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I+1)-
     1TEMP(I))
      GO TO 100
    3 IF(TEMP(I+1)-BOND)5,100,100
    5 ANS=(TEMP(I)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TEMP(I)-TEMP(I+1))+DEPTH
     1(I)
  100 CONTINUE
      IF(BOND.EQ.TEMP(N))ANS=DEPTH(N)
      RETURN
      END
```

```
$IBFTC SAVE
      SUBROUTINE SAVE(SAVE1,SAVE2,SAVE3,USE,NX1,VALUE,DT,TFINAL,TIME,
     1THING)
      DIMENSION SAVE1(1),SAVE2(1),SAVE3(1)
      USE=0.0
      SAVE1(NX1)=VALUE
      NX2=NX1-1
      IF(NX2.EQ.0)NX2=3
      SAVE2(NX2)=VALUE
      NX3=NX2-1
      IF(NX3.EQ.0)NX3=3
      SAVE3(NX3)=VALUE
      IF((TIME.LT.(2.*DT)).OR.(TIME.GE.(TFINAL-3.*DT)))GO TO 4
      GO TO (1,2,3),NX1
    1 IF(((ABS(SAVE2(1)-SAVE2(2))).LE..001).OR.(ABS(SAVE2(2)-SAVE2(3))
     1.LE..001))GO TO 5
      IF(((SAVE2(1).LT.SAVE2(2)).AND.(SAVE2(2).GT.SAVE2(3))).OR.((SAVE2(
     11).GT.SAVE2(2)).AND.(SAVE2(2).LT.SAVE2(3))))USE=SAVE2(2)
    5 THING=SAVE2(2)
      GO TO 4
    2 IF(((ABS(SAVE3(1)-SAVE3(2))).LE..001).OR.(ABS(SAVE3(2)-SAVE3(3))
     1.LE..001))GO TO 6
      IF(((SAVE3(1).LT.SAVE3(2)).AND.(SAVE3(2).GT.SAVE3(3))).OR.((SAVE3(
     11).GT.SAVE3(2)).AND.(SAVE3(2).LT.SAVE3(3))))USE=SAVE3(2)
    6 THING=SAVE3(2)
      GO TO 4
    3 IF(((ABS(SAVE1(1)-SAVE1(2))).LE..001).OR.(ABS(SAVE1(2)-SAVE1(3))
     1.LE..001))GO TO 6
      IF(((SAVE1(1).LT.SAVE1(2)).AND.(SAVE1(2).GT.SAVE1(3))).OR.((SAVE1(
     11).GT.SAVE1(2)).AND.(SAVE1(2).LT.SAVE1(3))))USE=SAVE1(2)
    7 THING=SAVE1(2)
    4 NX1=NX1+1
      IF(NX1.EQ.4)NX1=1
      RETURN
      END
```

```
$IBFTC DISCT3
      SUBROUTINE DISCT3(XA,TABX,TABY,NY,ANS)
      DIMENSION TABX(1),TABY(1)
      CALL DISSER(XA,TABX,1,NY,2,NN)
      NNN=3
      CALL LAGRAN(XA,TABX(NN),TABY(NN),NNN,ANS)
      RETURN
      END
```

```
$IBFTC MORE
      DIMENSION TITLE(12),X(2000),Y1(2000),Y2(2000),Y3(2000),Y4(2000)
      REWIND 11
      READ(11) (TITLE(I),I=1,12)
      READ(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      Y3(1)=Y3(1)*12.+Y1(1)
      Y4(1)=Y4(1)*12.+Y1(1)
      I=2
   30 READ(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)
      IF(X(I)-5001.)10,20,20
   10 Y3(I)=Y3(I)*12.+Y1(I)
      Y4(I)=Y4(I)*12.+Y1(I)
      I=I+1
      GO TO 30
   20 NPLOT=I-1
      YM1=Y1(1)
      YM2=Y2(1)
      YM3=Y3(1)
      YM4=Y4(1)
      DO 40 K = 2 , NPLOT
      IF (Y1(K).GT.YM1) YM1 = Y1(K)
      IF (Y2(K).GT.YM2) YM2 = Y2(K)
      IF (Y3(K).GT.YM3) YM3 = Y3(K)
      IF (Y4(K).GT.YM4) YM4 = Y4(K)
   40 CONTINUE
 1000 FORMAT(1H1,(12A6))
      CALL ACCEND(X,Y1,Y2,Y3,Y4,NPLOT)
      XMAX=X(NPLOT)
       CALL APLOT (X,Y1,XMAX,YM1,TITLE,NPLOT)
      CALL BPLOT (X,Y2,XMAX,YM2,TITLE)
      CALL CPLOT (X,Y3,Y4,XMAX,YM3,YM4,TITLE,Y1)
      WRITE(6,1000)(TITLE(I),I=1,12)
      WRITE(6,1001)(X(I),Y1(I),Y2(I),Y3(I),Y4(I),I=1,NPLOT)
 1001 FORMAT(5E20.8)
      WRITE(6,1002)XMAX,YM1,YM2,YM3,YM4,NPLOT
 1002 FORMAT(///6H XMAX=F10.4,5H YM1=F10.4,5H YM2=F10.4,5H YM3=F10.4,5H
     1YM4=F10.4,2X6HNPLOT=I4)
      READ (11) (TITLE (I),I = 1,12)
      READ(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      I=2
      IF(X(1)-5001.)30,50,50
   50 WRITE(6,1003)(TITLE(I),I=1,12)
 1003 FORMAT(////12A6)
      RETURN
      END
```

```
$IBFTC ACCEN
      SUBROUTINE ACCEND(X,Y,A,B,C,N)
      DIMENSION X(1),Y(1),A(1),B(1),C(1)
      K=1
  101 SMALL=X(K)
      DO 100 I=K,N
      DUMY=X(I)
      SMALL=AMIN1(SMALL,DUMY)
      IF(SMALL.EQ.X(I))INDEX=I
  100 CONTINUE
      X(INDEX)=X(K)
      X(K)=SMALL
      SAVE=Y(K)
      Y(K)=Y(INDEX)
      Y(INDEX)=SAVE
      SAVEA=A(K)
      A(K)=A(INDEX)
      A(INDEX)=SAVEA
      SAVEB=B(K)
      B(K)=B(INDEX)
      B(INDEX)=SAVEB
      SAVEC=C(K)
      C(K)=C(INDEX)
      C(INDEX)=SAVEC
      K=K+1
      IF(K.EQ.N)RETURN
      GO TO 101
      END
```

```
$IBFTC APLOT
      SUBROUTINE APLOT (X,Y,XLIM,YLIM,TITLE,IPLOT)
      DIMENSION X(300),YTITLE(10),XTITLE(10)
      DIMENSION TITLE(12),Y(300),ALONGY(7)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (XTITLE(I),I=1,10)/38H                          TIME (SEC.)   /
      DATA (YTITLE(I),I=1,10)/38H     SURFACE RECESSION (IN.)            /
      ZERO=0.0
      ALLOW(1)=50.
      ALLOW(2)=100.
      ALLOW(3)=250.
      ALLOW(4)=500.
      ALLOW(5)=1000.
      ALLOW(6)=2500.
      ALLOW(7)=5000.
      NPLOT=IPLOT
      DO 10 I=1,7
      II=I
      IF(XLIM- ALLOW(I)) 20,20,10
   10 CONTINUE
   30 WRITE (6,1000) XLIM,YLIM
 1000 FORMAT(///77H APLOT CANNOT BE DONE BECAUSE EITHER XLIM EXCEEDED 50
     100. OR YLIM EXCEEDED 5. /6H XLIM=E12.5,5X,6H YLIM=E12.5 // 19H WE
     2NOW GO TO BPLOT /// )
      RETURN
   20 XMAX= ALLOW(II)
      IFIX=II
      DO 40 I=1,4
      II=I
      IF(YLIM *100. -ALLOW(I) )50,50,40
   40 CONTINUE
      GO TO 30
   50 YMAX =ALLOW(II) /100.
      CALL RSTFRM
      CALL GRIDGN (123,1023,24,924,18,18,5,5)
      CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y,NPLOT,1,1H/)
      ALONGX(1)=0.0
      ALONGY(1)=0.0
      DO 60 I=1,6
      CALL LABELX (ALONGX(I),1)
      CALL LABELY (ALONGY(I),1)
      ALONGX(I+1)= ALONGX(I) +.2* XMAX
   60 ALONGY(I+1)= ALONGY(I) +.2* YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

```
$IBFTC BPLOT
      SUBROUTINE BPLOT (X,Y,XLIM,YLIM,TITLE)
      DIMENSION X(300),Y(300),YTITLE(10),ALONGY(7),XTITLE(10)
      DIMENSION TITLE(12)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (XTITLE(I),I=1,10)/38H                          TIME (SEC.)    /
      DATA (YTITLE(I),I=1,10)/38H          BONDLINE TEMPERATURE (R)    /
      ALONGY(1)=0.0
      DO 10 I=1,7
      II=I
      IF(YLIM -ALLOW(I)) 20,20,10
   10 CONTINUE
      WRITE (6,1000) YLIM
 1000 FORMAT(/// 37H BPLOT WILL NOT BE DONE BECAUSE YLIM= E12.5 ////)
      RETURN
   20 YMAX =ALLOW(II)
      CALL RSTFRM
      CALL GRIDGN(123,1023,24,924,18,18,5,5 )
      CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y, NPLOT,1, 1H/ )
      DO 30 I=1,6
      CALL LABELX (ALONGX(I),1)
      CALL LABELY (ALONGY(I),1)
   30 ALONGY(I+1) = ALONGY(I) + .2* YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

```
$IBFTC CPLOT
      SUBROUTINE CPLOT (X,Y1,Y2,XLIM,YLIM1,YLIM2,TITLE, Y)
      DIMENSION X(300),Y1(300),Y2(300),YTITLE(10),YY(2000),XTITLE(10)
      DIMENSION TITLE(12),Y(300),ALONGY(7)
      DIMENSION CURVE(1),VBUG(4),HBUG(7)
      COMMON /ABC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,IFIX
      DATA (VBUG(I),I=1,4) / 100.0,50.0,20.0,10.0  /
      DATA (HBUG(I),I=1,7) / 1.0,2.0,5.0,10.0,20.0,50.0,100.0 /
      DATA (XTITLE(I),I=1,10)/38H                          TIME (SEC.)    /
      DATA (YTITLE(I),I=1,10)/38H      DISTANCE (IN.)                     /
      DATA ONE/4H1060 /,TWO/4H1460 /
      DATA WON/1H1 /,TOO/1H2  /
C *** FOUR (4) CHARACTERS ARE ALLOWED FOR CURVE(1)
      CURVE(1)=ONE
      HFACTR=HBUG(IFIX)
      SYMBOL=WON
      YBIG =AMAX1 (YLIM1,YLIM2 )
      NCURVE =1
      DO 1 I=1,NPLOT
    1 YY(I)= Y1(I)
      DO 7 I=1,4
      II= I
      IF(YBIG*100. -ALLOW(I))6,6,7
    7 CONTINUE
      WRITE (6,1000) YLIM1,YLIM2
 1000 FORMAT (/// 38H CPLOT WILL NOT BE DONE BECAUSE YLIM1=F12.5,10H OR
     1YLIM2= E12.5 //// )
      RETURN
    6 YMAX =ALLOW (II)/100.
      VFACTR=VBUG(II)
      CALL RSTERM
      CALL GRIDGN (123,1023,24,924,18,18,5,5)
      J=1
   70 DO 10 I=J,NPLOT
      II= I
      IM1 =I-1
      IF( YY(I)-Y(I) )20,10,10
   10 CONTINUE
      NOPT=NPLOT-J+1
      LL=J + NOPT/2
      IVLOC=(YMAX-YY(LL))*18.*VFACTR  +24. -4.
      IHLOC= X(LL)*18. /HFACTR  +123. -48.
      CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)
      CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NOPT ,1,SYMBOL)
      IF (NCURVE-1 ) 90,85,90
   85 DO 86 I=1,NPLOT
   86 YY(I)=Y2(I)
      CURVE(1)=TWO
      SYMBOL=TOO
      NCURVE = 2
      J=1
      GO TO 70
   20 NPT=II-J
      LL=J +  NPT/2
      IVLOC=(YMAX-YY(LL))*18.*VFACTR  +24. -4.
      IHLOC= X(LL)*18. /HFACTR  +123. -48.
      CALL PRINT(IHLOC,IVLOC, 8,0,4,CURVE)
```

```
      CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NPT,1,SYMBOL)
      DO 50 IJ= II, NPLOT
      JJ= IJ
      IF(YY(IJ)- Y(IJ) )50,40,40
   50 CONTINUE
      IF(NCURVE-1) 90,85,90
   40 J= JJ
      GO TO 70
   90 ALONGY(1)=0.0
      DO 100 I=1,6
      CALL LABELX(ALONGX(I), 1)
      CALL LABELY(ALONGY(I),1)
  100 ALONGY(I+1)=ALONGY(I) + .2*YMAX
      CALL PRINT(200,975,12,0,38,XTITLE)
      CALL PRINT(47,200,0,12,38,YTITLE)
      CALL PRINT(123,1000,12,0,72,TITLE)
      CALL DMPBUF
      RETURN
      END
```

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APPENDIX C

PROGRAM TERMINOLOGY

Fortran	Description
A	"A" coefficient in matrix, single subscript
AB	"A" coefficient in matrix, double subscript
ABLC	specific heat of material at TABL
ABLK	thermal conductivity of material at TABL
B	"B" coefficient in matrix, single subscript
BB	"B" coefficient in matrix, double subscript
BL	Total thickness of backup structure
BLTEM	value of 1460 isotherm depth from previous time step
BTEST	test to determine mode of heat transfer out of back surface of backup materials
C	"C" coefficient in matrix, single subscript
CB	"C" coefficient in matrix, double subscript
CHARC	specific heat of material at TCHAR
CHARK	thermal conductivity of material at TCHAR
CP	specific heat of a node in ablation material
CPB	specific heat of backup material node
CPC	specific heat values in char specific heat table
CPV	specific heat values in virgin specific heat table
CPX	specific heat values in backup material specific heat tables

Fortran	Description
D	"D" coefficient in matrix, single subscript
DB	"D" coefficient in matrix, double subscript
DELTT	time step in the time step table
DMP	test used for dumping (DMP = 0 skip dump, DMP = 1.0 start dumping)
DRHØ	local mass flow rate of ablation gas
DT	time step from the time step table in hours
DTS	time step from time step table in seconds
DX	thickness of a node in the ablation material
DXB	thickness of a node in a backup structure material
DXV	variable ablation node thickness $\left(= \frac{VLV}{NP - 1}\right)$
DXX	fixed ablation material node thickness $\left(= \frac{VLI}{NP - 1}\right)$
EMBB	emissivity of back surface of each material in backup
EMC	char material emissivity
EMFB	emissivity of front surface of each material in backup
EMV	virgin material emissivity
EMX	emissivity of front surface of ablation material
END	code word for plot routine
ERR1, ERR2, ERR3, ERR4	Control numbers for printing error statements when an input or calculational mistake is made

Fortran	Description
FBLØW	blowing efficiency in reducing convective heating
FCØNV	factor to correct convective heating rate for various body locations
FENV	emissivity – view factor product to cabin interior
FRAD	factor to correct radiative heating rate for various body locations
FTEST	test to determine mode of heat transfer into front surface of backup materials
FV	view factor for external environment
G	defined by Fortran statement
GAPX	gap width between backup materials
H	film coefficient between backup materials
H300	enthalpy of air at 300° K
HEAD	any 72 alphanumeric characters used to identify problems being run – printed at top of first page of output
HEADNG	any 72 alphanumeric characters used to identify each input section
HENV	film coefficient to cabin environment
HTX	total enthalpy
HV	heat of degradation of virgin material
HW	wall enthalpy computed from enthalpy – temperature table
HX	enthalpy values in enthalpy table
IEM	test used to determine if front surface is virgin or char for using proper emissivity
IPRC	variable print frequency in time-step table
IPRCT	present print control number

Fortran	Description
IR	test to determine if node temperature is greater than TABL
IR1	test used in determining node density at TX1 temperature
IR2	test used in determining node density at TX2 temperature
NCASE	number of problems to be run
NCPB	number of points in each backup material specific heat table
NCPC	number of points in char specific heat temperature table
NCPV	number of points in virgin specific heat temperature table
NKC	number of points in char thermal conductivity – temperature table
NKPB	number of points in each backup material thermal conductivity table
NKV	number of points in virgin thermal conductivity temperature table
NMB	number of materials in backup structure
NP	number of node points in ablation material
NPBS	total number of node points in backup structure
NPF	total number of points in heat shield structure (NP + NPBS)
NPLØT	output plot control number
NPM	number of nodes per material in backup
NHP	number of points in enthalpy – temperature table
NPTT	number of points in time-step table
NREC	number of points in surface recession – temperature or time table
NTRAPT	number of points in trajectory input table

Fortran	Description
NXA NXB NXC NXD NXE	dummy indexes for subroutine Save
QBLØCK	amount of convective heat blocked due to mass injection into boundary layer
QCØN	trajectory table convective heating rates
QCØNX	cold wall convective heat rate at present time step
QHW	hot wall convective heat rate without blowing
QIN	net heat flux into front surface
QLØSS	boundary condition for heat transfer to cabin interior
QØXID	heating rate due to combustion
QRAD	trajectory table radiative heating rates
QRADX	radiative heat flux at present time step
QUIT	code word for plot routine
R	thermal resistance due to conductivity between nodes in the ablation material
RB1	thermal resistance due to conductivity between past and present node in backup material
RB2	thermal resistance due to conductivity between present and forward node in backup material
RHØ	density of an ablation material node
RHØBX	density of individual materials in backup
RHØC	mature char material density

Fortran	Description
RHØV	virgin ablation material density
RHØY1	density of node at past time step
RHØY2	density of node at present time step
S	thermal capacity of a node in the ablation material
SDØT	surface recession rate
SAVEIT	depth of 1060 isotherm at any given time
SAVEXX	time corresponding to maximum depth of 1460 isotherm
SAVX	time corresponding to maximum depth of 1060 isotherm
SAVY1	surface recession depth at maximum 1060 isotherm depth
SAVY2	bondline temperature at maximum 1060 isotherm depth
SAVY3	term that will contain maximum depth of 1060 isotherm
SAVY4	depth of 1460 isotherm at maximum 1060 isotherm depth
SAVY1X	surface recession depth at maximum 1460 isotherm depth
SAVY2X	bondline temperature at maximum 1460 isotherm depth
SAVY3X	depth of 1060 isotherm at maximum 1460 isotherm depth
SAVY4X	term that will contain maximum depth of 1460 isotherm
SR	surface recession values in surface recession table
T	present time
TABL	temperature at which ablation starts
TCHAR	temperature at which ablation stops
TCP	temperature values in backup material specific heat tables
TCPC	temperature values in char specific heat table
TCPV	temperature values in virgin specific heat table

Fortran	Description
TEMDI	arbitrary initial temperature distribution values
TEMPI	constant initial temperature distribution value
TENV	interior cabin temperature
TEST2	test to determine proper heat shield initial temperature distribution
TDMP	time to start dumping or printing information used in check-out of program (sets DMP = 1.0)
TIME	trajectory table time values
TINT	starting time of problem
TITLE	control card used for reading in new data for successive problems
TKC	temperature values in char thermal conductivity table
TKV	temperature values in virgin thermal conductivity table
TL	total thickness of heat shield structure (VL + BL)
TLIM	time limit of problem
TREC	surface temperature or time at which char removal is to start
TS	temperature or time values in surface recession table
TTABLE	time values in time-step table
TTUL	equals TUL if VPT = 0 or equals TX2 if VPT = 1 — used in computing char properties
TUL	maximum value of TX1 and TX2
TUL1	maximum TX1 values — used in computing gas ablation rate
TUL2	maximum TX2 values — used in computing gas ablation rate
TV	sink temperature of external environment
TW	temperature values in enthalpy table

Fortran	Description
TX1	temperature of nodes at past time step
TX2	temperature of nodes at present time step
TX2C	temperature at fixed locations in ablation material as defined by XC
TX2T	temporary storage of TX2 temperatures for computing thermal properties
TXK	temperature values in backup material thermal conductivity tables
TXØ	initial temperature at front surface of heat shield for computing linear temperature gradient
TY	temperature distribution at forward time step
VEL	trajectory table velocity values
VELX	trajectory velocity at present time step
VL	initial virgin material thickness
VLI	initial ablation material thickness
VLTEM	value of 1060 isotherm depth from previous time step
VLV	variable ablation material thickness
VPT	test to determine if properties are irreversible with temperature
WEKEEP	depth of 1460 isotherm at any time
XBM	thickness of individual materials in backup
XC	fixed location of nodes in the ablation material
XI	node number
XIDNT	any 72 alphanumeric characters to identify each material
XK	thermal conductivity values in backup material thermal conductivity table

Fortran	Description
XKB	thermal conductivity of backup material node
XKC	thermal conductivity in char thermal conductivity table
XKV	thermal conductivity value in virgin thermal conductivity table
XLØST	amount of solid ablation material lost in a time step due to surface movement
XLSTI	distance from original surface to present front surface location, inches
XLSTV	distance from original surface to present front surface location, feet
XMDC	mass loss rate of char
XMDG	mass gas ablation rate due to pyrolysis of virgin material
XMDØ	mass flux rate of oxygen to surface
XMDT	total ablation rate
XNP	number of nodes in ablation material
XNPM	number of nodes per backup material
XPLØT	time to be written on tape and plotted
XV	location of nodes in variable ablation material thickness
YK	thermal conductivity of a node in ablation material
YPLØT1	recession depth to be written on tape and plotted
YPLØT2	bondline temperature to be written on tape and plotted
YPLØT3	1060 isotherm depth to be written on tape and plotted
YPLØT4	1460 isotherm depth to be written on tape and plotted
ZZZ	ratio to determine when the limiting value of heat blockage has been reached

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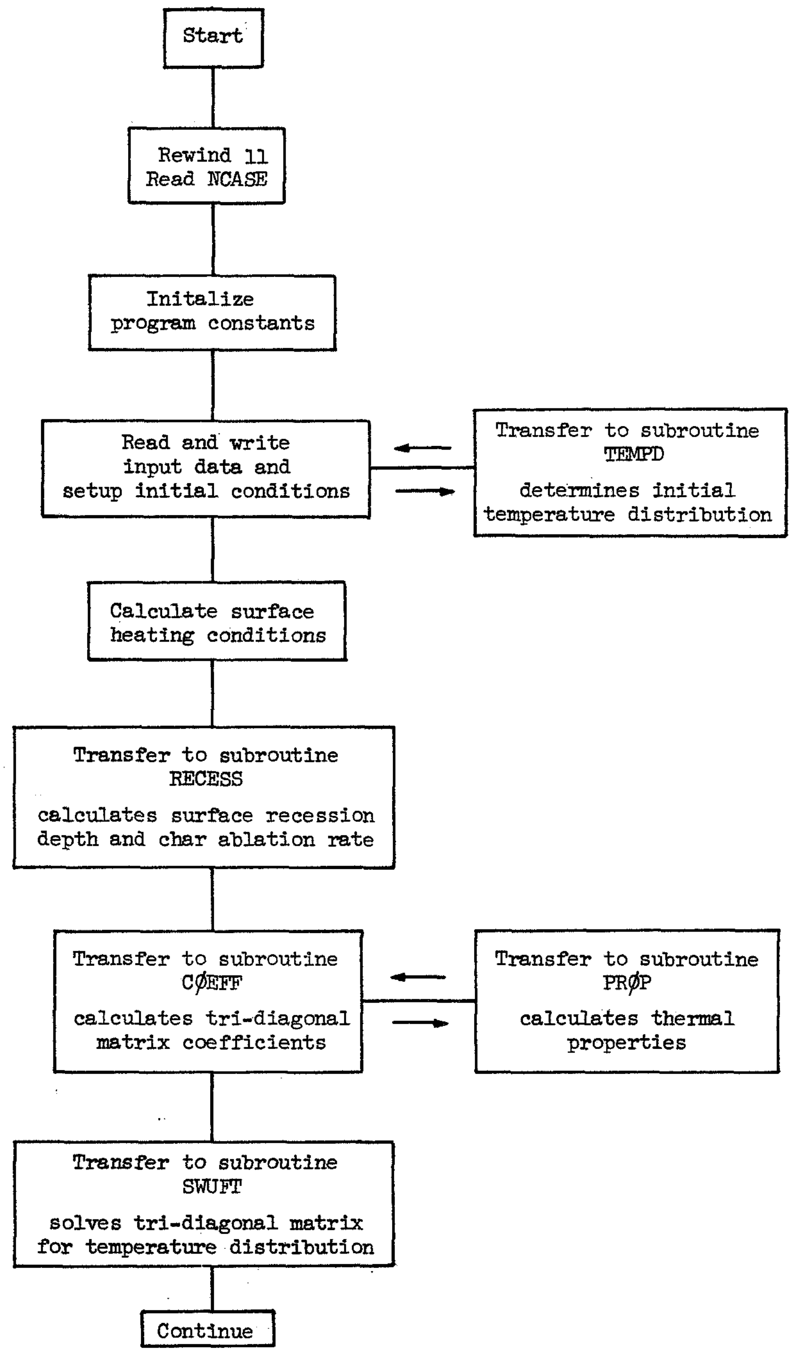
APPENDIX D

GENERAL FLOW CHART



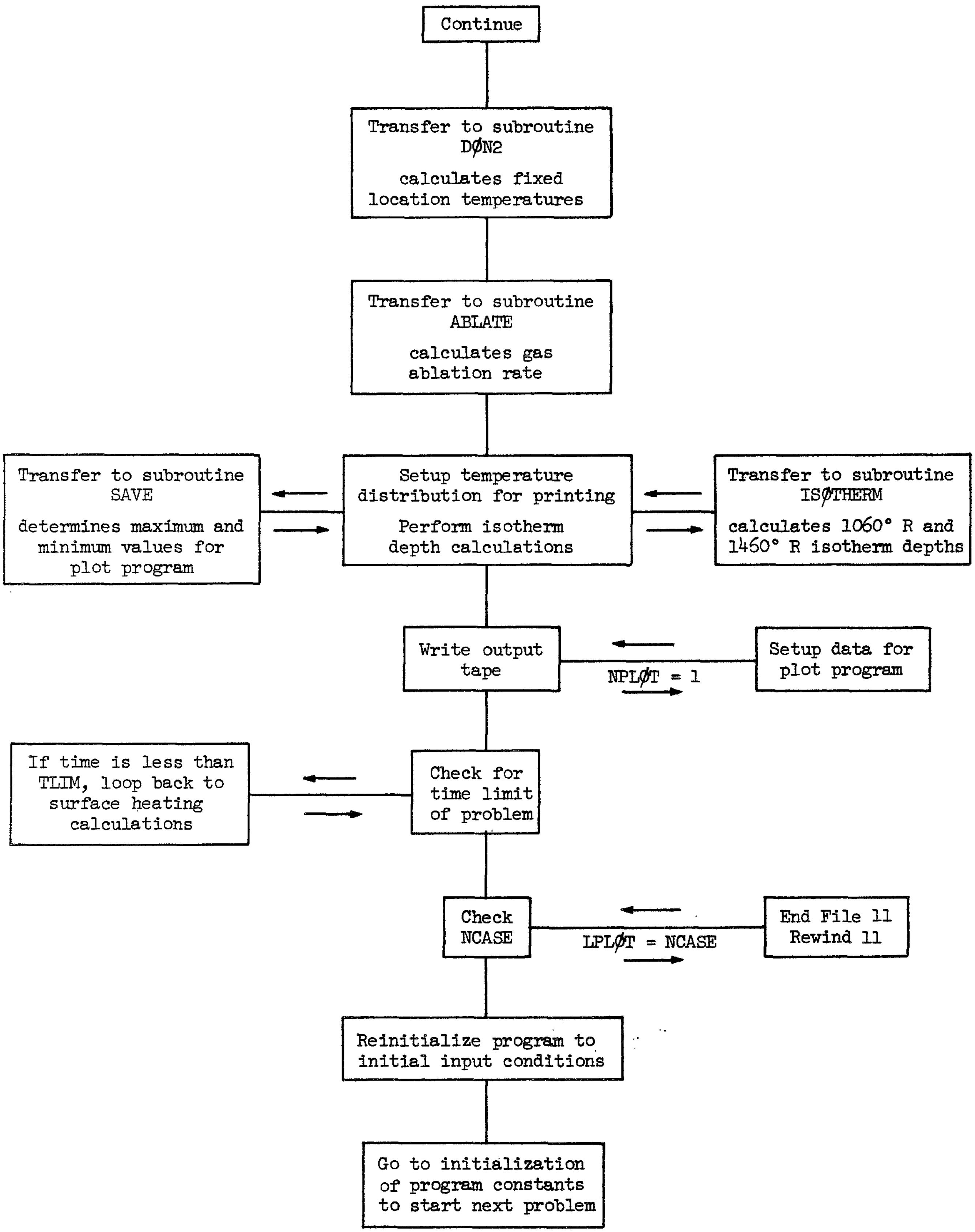

Continue
Transfer to subroutine D∅N2
calculates fixed location temperatures
Transfer to subroutine ABLATE
calculates gas ablation rate
Transfer to subroutine SAVE
determines maximum and minimum values for plot program
Setup temperature distribution for printing
Perform isotherm depth calculations
Transfer to subroutine IS∅THERM
calculates 1060° R and 1460° R isotherm depths
Write output tape
NPL∅T = 1
Setup data for plot program
If time is less than TLIM, loop back to surface heating calculations
Check for time limit of problem
Check NCASE
LPL∅T = NCASE
End File 11
Rewind 11
Reinitialize program to initial input conditions
Go to initialization of program constants to start next problem

TABLE I.- SAMPLE PROBLEM INPUT

(a) Coding sheet

```
 1
  TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65    DONALD M. CURRY
+600.0   +00 +0.0     +00       2      1
+0.0     +00 +0.1     +00     100
+600.0   +00 +0.1     +00     100

+1.0     +00 +1.0     +00

  TYPICAL CHARRING ABLATION MATERIAL PROPERTIES
+1060.0  +00 +1460.0  +00 +0.0     +00 +34.0    +00 +20.0    +00 +0.0     +00
+0.65    +00 +0.75    +00 +129.06  +00 +1.5     +00 +250.0   +00 +0.0     +00
+1.0     +00 +0.0     +00 +0.12    +00 +0.43    +00 +0.070   +00 +0.43    +00
  31       2     2      9     2      2
+1460.0  +00 +0.12    +00 +1.0     +04 +0.12    +00
+1460.0  +00 +0.43    +00 +1.0     +04 +0.43    +00
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655  +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672  +00 +860.0   +00 +0.0684  +00
+960.0   +00 +0.069   +00 +1060.0  +00 +0.070   +00 +1160.0  +00 +0.070   +00
+360.0   +00 +0.43    +00 +1100.0  +00 +0.43    +00
+0.0     +00 +9.0     -04 +600.0   +00 +9.0     -04

  NO TRAJECTORY - Q=95 BTU/SEC-SQFT
  2
+0.0     +00 +95.0    +00 +0.0     +00 +2.925   +04
```

```
+600.0   +00 +95.0    +00 +0.0     +00 +2.925   +04

    1      3  +0.1    +00
+3.0       +00
    9      2
   BACKUP MATERIAL                 0.1 INCHES THICK
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655  +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672  +00 +860.0   +00 +0.0684  +00
+960.0   +00 +0.069   +00 +1060.0  +00 +0.07    +00 +1160.0  +00 +0.07    +00
+360.0   +00 +0.43    +00 +1100.0  +00 +0.43    +00
+34.0    +00 +0.1     +00 +0.9     +00 +0.9     +00
+0.0     +00 +0.0     +00 +0.0     +00 +0.0     +00

  HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0
+560.0   +00 +0.0     +00 +0.0     +00 +0.0     +00

  INITIAL TEMPERATURE IS CONSTANT
+0.0     +00 +530.0   +00 +530.0   +00

  42
+0.0     +00 +0.0     +00 +342.9   +00 +1400.0  +00 +449.7   +00 +1800.0  +00
+617.2   +00 +2400.0  +00 +791.0   +00 +3000.0  +00 +978.0   +00 +3600.0  +00
+1113.0  +00 +4006.0  +00 +1200.0  +00 +4224.0  +00 +1300.0  +00 +4486.0  +00
+1400.0  +00 +4723.0  +00 +1500.0  +00 +4936.0  +00 +1600.0  +00 +5127.0  +00
+1700.0  +00 +5299.0  +00 +1800.0  +00 +5454.0  +00 +1900.0  +00 +5596.0  +00
```

+2000.0	+00	+5728.0	+00	+2100.0	+00	+5851.0	+00	+2200.0	+00	+5968.0	+00
+2300.0	+00	+6078.0	+00	+2400.0	+00	+6186.0	+00	+2500.0	+00	+6291.0	+00
+2600.0	+00	+6395.0	+00	+2700.0	+00	+6497.0	+00	+2800.0	+00	+6597.0	+00
+2900.0	+00	+6699.0	+00	+3000.0	+00	+6805.0	+00	+3100.0	+00	+6918.0	+00
+3200.0	+00	+7050.0	+00	+3300.0	+00	+7175.0	+00	+3400.0	+00	+7350.0	+00
+3500.0	+00	+7480.0	+00	+3600.0	+00	+7630.0	+00	+3700.0	+00	+7800.0	+00
+3800.0	+00	+7970.0	+00	+3900.0	+00	+8120.0	+00	+4000.0	+00	+8300.0	+00
+4100.0	+00	+8500.0	+00	+4200.0	+00	+8700.0	+00	+4300.0	+00	+8850.0	+00
+4400.0	+00	+9000.0	+00	+4500.0	+00	+9150.0	+00	+4600.0	+00	+9270.0	+00

TABLE I.- SAMPLE PROBLEM INPUT

(b) Fortran data card listing

```
   1
    TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65    DONALD M. CURRY

+600.0   +00 +0.0     +00     2     1
+0.0     +00 +0.1     +00   100
+600.0   +00 +0.1     +00   100

+1.0     +00 +1.0     +00

   TYPICAL CHARRING ABLATION MATERIAL PROPERTIES
+1060.0 +00 +1460.0 +00 +0.0     +00 +34.0    +00 +20.0    +00 +0.00    +00
+0.65    +00 +0.75    +00 +129.06 +00 +1.50    +00 +250.0   +00 +0.0     +00
+1.0     +00 +0.0     +00 +0.12    +00 +0.43    +00 +0.070   +00 +0.43    +00
  31     2     2     0     2     2
+1460.0 +00 +0.12    +00 +1.0     +04 +0.12    +00
+1460.0 +00 +0.43    +00 +1.0     +04 +0.43    +00
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655 +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672 +00 +860.0   +00 +0.0684 +00
+960.0   +00 +0.069   +00 +1060.0 +00 +0.070   +00 +1160.0 +00 +0.070   +00
+360.00  +00 +0.43    +00 +1100.0 +00 +0.43    +00
+0.0     +00 +9.0     -04 +600.0   +00 +9.0     -04

   NO TRAJECTORY - Q=95 BTU/SEC-SQFT
   2
+0.0     +00 +95.0    +00 +0.0     +00 +2.925   +04
+600.0   +00 +95.0    +00 +0.0     +00 +2.925   +04

   1     3   +0.1     +00
+5.0     +00
   9     2
   BACKUP MATERIAL                      0.1 INCHES THICK
+360.0   +00 +0.065   +00 +460.0   +00 +0.065   +00 +560.0   +00 +0.0655 +00
+660.0   +00 +0.066   +00 +760.0   +00 +0.0672 +00 +860.0   +00 +0.0684 +00
+960.0   +00 +0.069   +00 +1060.0 +00 +0.07    +00 +1160.0 +00 +0.07    +00
+360.00  +00 +0.43    +00 +1100.0 +00 +0.43    +00
+34.0    +00 +0.1     +00 +0.9     +00 +0.9     +00
+0.0     +00 +0.0     +00 +0.0     +00 +0.0     +00

 HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0
+560.0   +00 +0.0     +00 +0.0     +00 +0.0     +00

 INITIAL TEMPERATURE IS CONSTANT
+0.0     +00 +530.0   +00 +530.0   +00

  42
+0.0     +00 +0.0     +00 +342.9   +00 +1400.0 +00 +449.7   +00 +1800.0 +00
+617.2   +00 +2400.0 +00 +791.0   +00 +3000.0 +00 +978.0   +00 +3600.0 +00
+1113.0 +00 +4000.0 +00 +1200.0 +00 +4224.0 +00 +1300.0 +00 +4486.0 +00
+1400.0 +00 +4723.0 +00 +1500.0 +00 +4936.0 +00 +1600.0 +00 +5127.0 +00
+1700.0 +00 +5299.0 +00 +1800.0 +00 +5454.0 +00 +1900.0 +00 +5596.0 +00
+2000.0 +00 +5728.0 +00 +2100.0 +00 +5851.0 +00 +2200.0 +00 +5968.0 +00
+2300.0 +00 +6078.0 +00 +2400.0 +00 +6186.0 +00 +2500.0 +00 +6291.0 +00
+2600.0 +00 +6395.0 +00 +2700.0 +00 +6497.0 +00 +2800.0 +00 +6597.0 +00
+2900.0 +00 +6699.0 +00 +3000.0 +00 +6805.0 +00 +3100.0 +00 +6918.0 +00
```

+3200.0	+00+7050.0	+00+3300.0	+00+7175.0	+00+3400.0	+00+7350.0	+00
+3500.0	+00+7480.0	+00+3600.0	+00+7630.0	+00+3700.0	+00+7800.0	+00
+3800.0	+00+7470.0	+00+3900.0	+00+8120.0	+00+4000.0	+00+8300.0	+00
+4100.0	+00+8600.0	+00+4200.0	+00+8700.0	+00+4300.0	+00+8850.0	+00
+4400.0	+00+9000.0	+00+4500.0	+00+9150.0	+00+4600.0	+00+9270.00	+00

TABLE II.- SAMPLE PROBLEM OUTPUT

TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65 DONALD M. CURRY

INPUT DATA.

TIME LIMIT=6.0000E 02 INITIAL TIME=0. NPTT= 2

TIME	TIME STEP	PRINT CONTROL
0.	1.0000E-01	100
6.0000E 02	1.0000E-01	100

FCONV= 1.00000E 00 FRAD= 1.00000E 00

TYPICAL CHARRING ABLATION MATERIAL PROPERTIES

TABL= 1.06000E 03 TCHAR= 1.46000E 03 TREC= 0. RHOV= 3.40000E 01 RHOC= 2.00000E 01
FBLOW= 0. EMV= 6.50000E-01 EMC= 7.50000E-01 H300= 1.29060E 02 VL= 1.50000E 00
HV= 2.50000E 02 VPT= 0. FV= 1.00000E 00 TV= 0. CHARK= 1.20000E-01
CHARC= 4.30000E-01 ABLK= 7.00000E-02 ABLC= 4.30000E-01

NP= 31 NKC= 2 NCPC= 2 NKV= 9 NCPV= 2 NREC= 2

VIRGIN MATERIAL

TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	SPECIFIC HEAT
3.60000E 02	6.50000E-02	3.60000E 02	4.30000E-01
4.60000E 02	6.50000E-02	1.10000E 03	4.30000E-01
5.60000E 02	6.55000E-02		
6.60000E 02	6.60000E-02		
7.60000E 02	6.72000E-02		
8.60000E 02	6.84000E-02		
9.60000E 02	6.90000E-02		
1.06000E 03	7.00000E-02		
1.16000E 03	7.00000E-02		

CHAR MATERIAL

TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	SPECIFIC HEAT
1.46000E 03	1.20000E-01	1.46000E 03	4.30000E-01
1.00000E 04	1.20000E-01	1.00000E 04	4.30000E-01

SURFACE RECESSION TABLE

TIME	SR - IN/SEC
0.	9.00000E-04
6.00000E 02	9.00000E-04

NO TRAJECTORY - Q=95 BTU/SEC-SQFT

NO. OF TRAJECTORY POINTS = 2

TIME	Q CONVECTIVE	Q RADIATIVE	VELOCITY
0.	9.50000E 01	0.	2.92500E 04
6.00000E 02	9.50000E 01	0.	2.92500E 04

PROPERTIES OF BACKUP STRUCTURE

NO. OF MATERIALS IN BACK-UP SHIELD= 1
TOTAL NUMBER OF NODES IN BACK-UP SHIELD= 3
THICKNESS OF BACK-UP SHIELD= 1.00000E-01

BACKUP MATERIAL 0.1 INCHES THICK

TEMPERATURE	THERMAL CONDUCTIVITY	TEMPERATURE	SPECIFIC HEAT
3.60000E 02	6.50000E-02	3.60000E 02	4.30000E-01
4.60000E 02	6.50000E-02	1.10000E 03	4.30000E-01
5.60000E 02	6.55000E-02		
6.60000E 02	6.60000E-02		
7.60000E 02	6.72000E-02		
8.60000E 02	6.84000E-02		
9.60000E 02	6.90000E-02		
1.06000E 03	7.00000E-02		
1.16000E 03	7.00000E-02		

MATERIAL	DENSITY	THICKNESS	EMISSIVITY FRONT	EMISSIVITY BACK	NODES/MATERIAL
1	3.4000E 01	1.0000E-01	9.0000E-01	9.0000E-01	3.0000E 00

ADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP STRUCTURE

MATERIAL	FILM COEFFICIENT	GAP THICKNESS	FTEST	BTEST
1	0.	0.	0.	0.

HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0

TEMPERATURE= 5.60000E 02 FILM COEFFICIENT= 0. VIEW FACTOR= 0. Q LOST= 0.

INITIAL TEMPERATURE IS CONSTANT

TEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM AND EQUAL TO 5.3000E 02

OUTPUT DATA.

TIME= 9.90000E 00 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0. VELOCITY= 2.92500E 04
GAS ABLATION RATE= 0. CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 5.40000E 00
RECESSION DEPTH= 9.00000E-03 QHOT WALL= 8.89893E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 1.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

4.25564E 03	2.70129E 03	1.19740E 03	6.43320E 02	5.43814E 02	5.31490E 02
5.30126E 02	5.30007E 02	5.30000E 02	5.29999E 02	5.30000E 02	5.30000E 02
5.30000E 02	5.30000E 02	5.29999E 02	5.30000E 02	5.30000E 02	5.30000E 02
5.30000E 02	5.30000E 02	5.30000E 02	5.30000E 02	5.30000E 02	5.30000E 02
5.30000E 02	5.30000E 02	5.30000E 02	5.29999E 02	5.30000E 02	5.30000E 02
5.29999E 02					

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

5.29999E 02	5.30000E 02	5.30000E 02

TIME= 1.99000E 01 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0. VELOCITY= 2.92500E 04
GAS ABLATION RATE= 0. CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 5.40000E 00
RECESSION DEPTH= 1.80000E-02 QHOT WALL= 8.89148E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 2.00000E 01 SECONDS

TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

4.26944E 03	3.15689E 03	1.77750E 03	1.02157E 03	6.89430E 02	5.66334E 02
5.37192E 02	5.31229E 02	5.30183E 02	5.30023E 02	5.30002E 02	5.30000E 02
5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02
5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02
5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02	5.29999E 02
5.29999E 02					

TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

5.29999E 02	5.29999E 02	5.29999E 02

TIME= 2.99000E 01 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0. VELOCITY= 2.92500E 04
GAS ABLATION RATE= 4.04922E 00 CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 9.44922E 00
RECESSION DEPTH= 2.70000E-02 QHOT WALL= 8.87279E 01

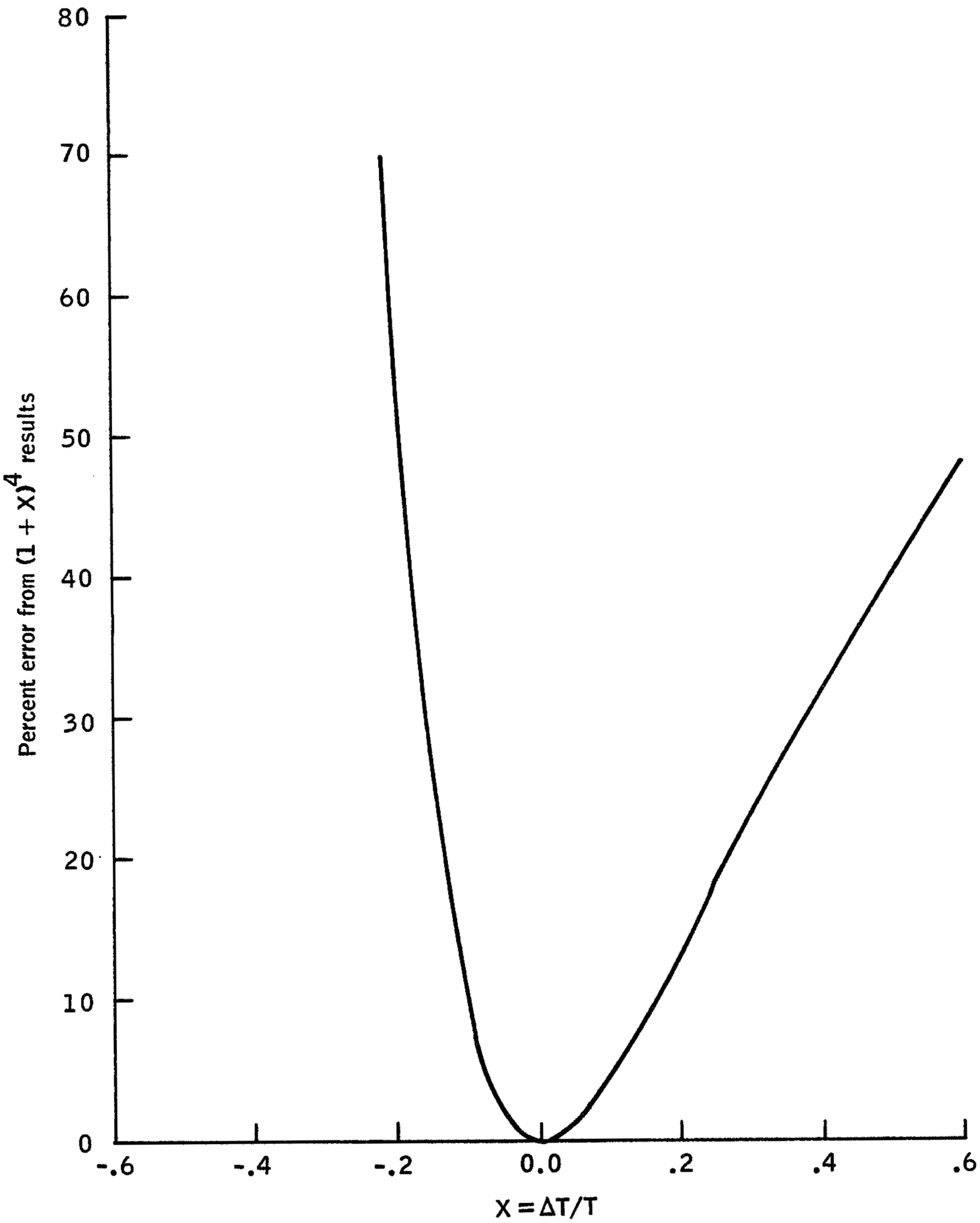


Figure 1.- Radiation temperature approximation error.

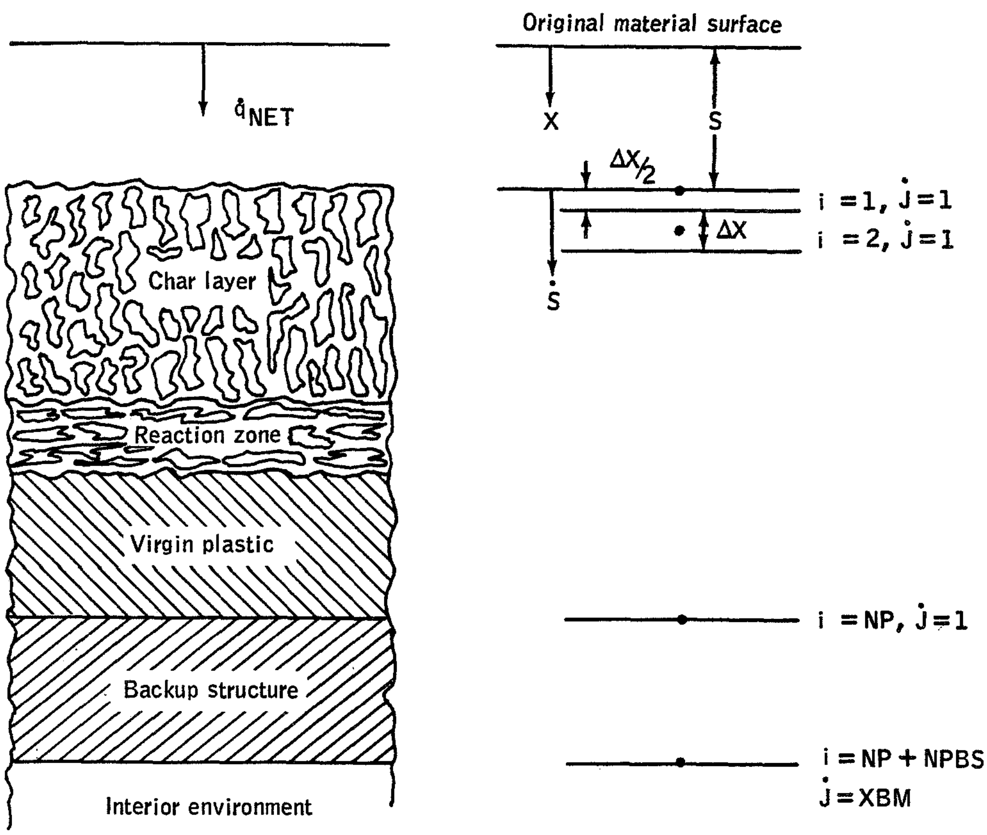


Figure 2.- Schematic diagram of charring ablator thermal protection system.

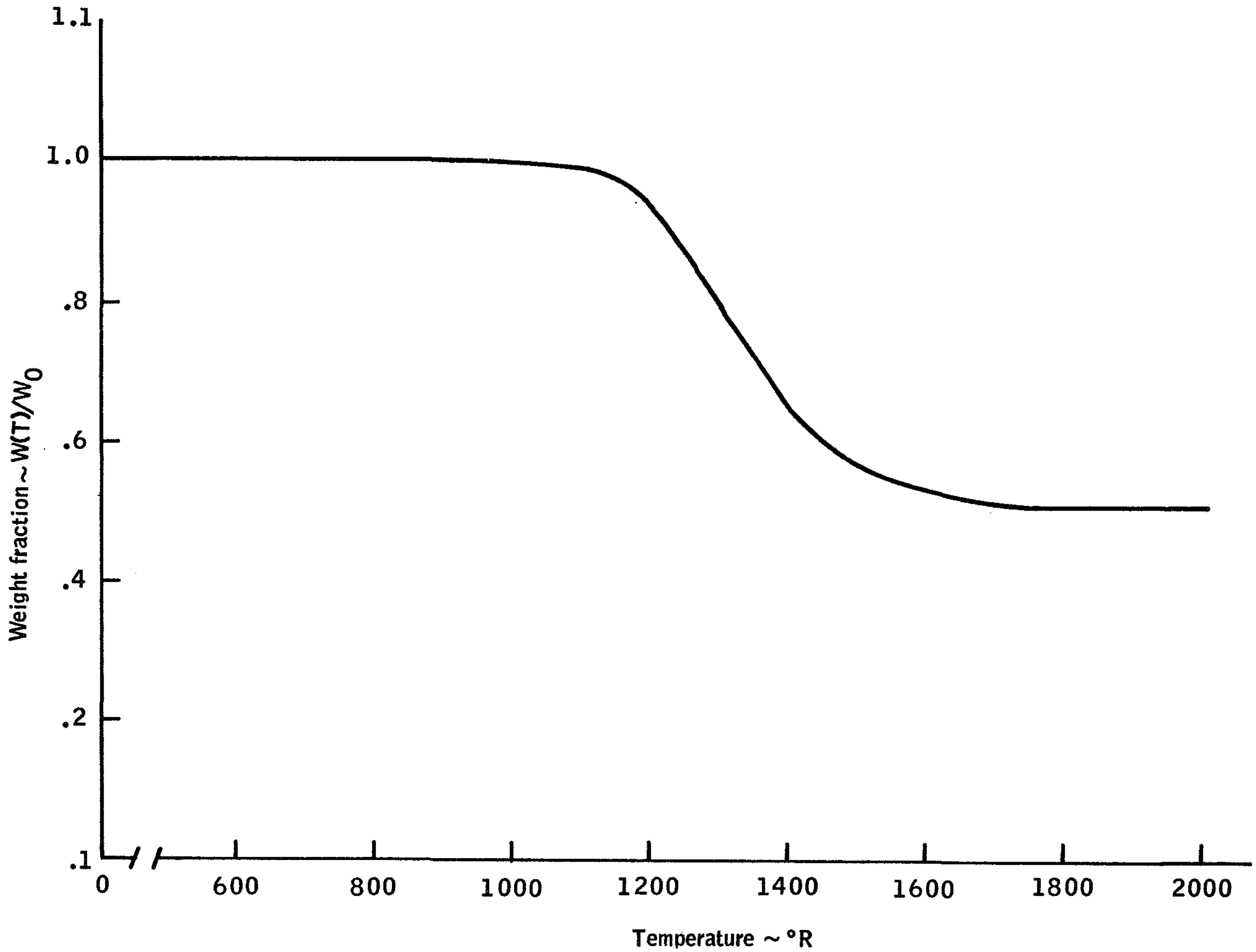


Figure 3.- Thermogravimetric data for typical charring ablation material

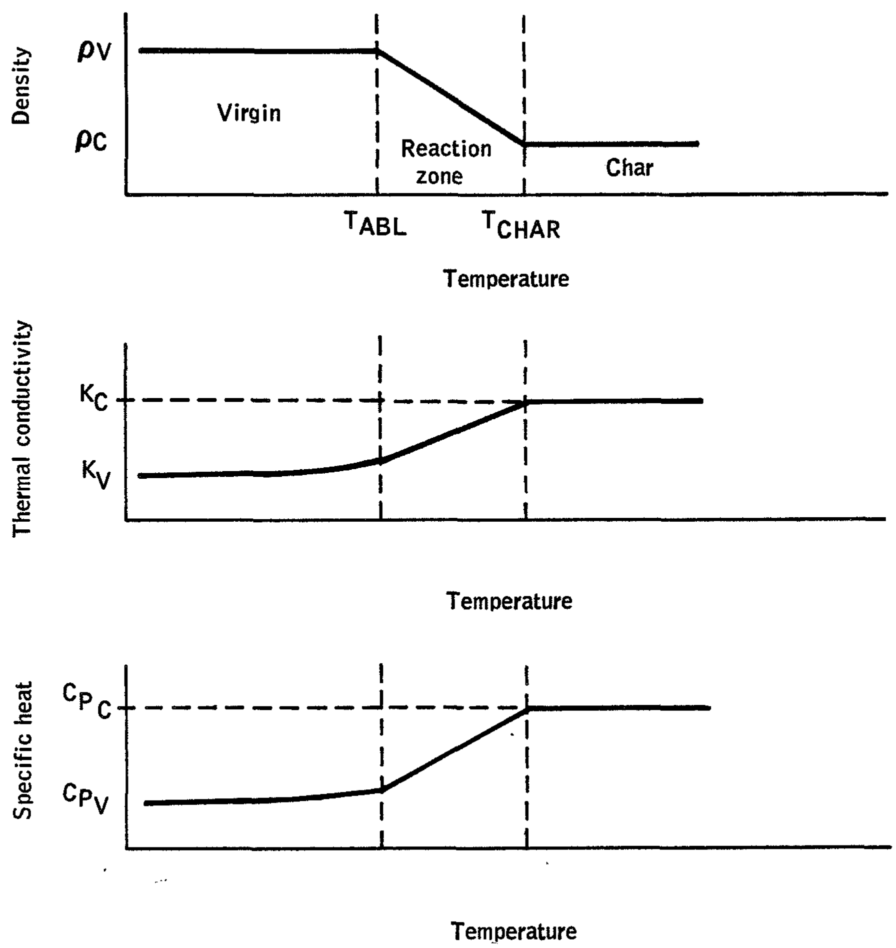


Figure 4.- Charring material property variation used as input to STAB II.

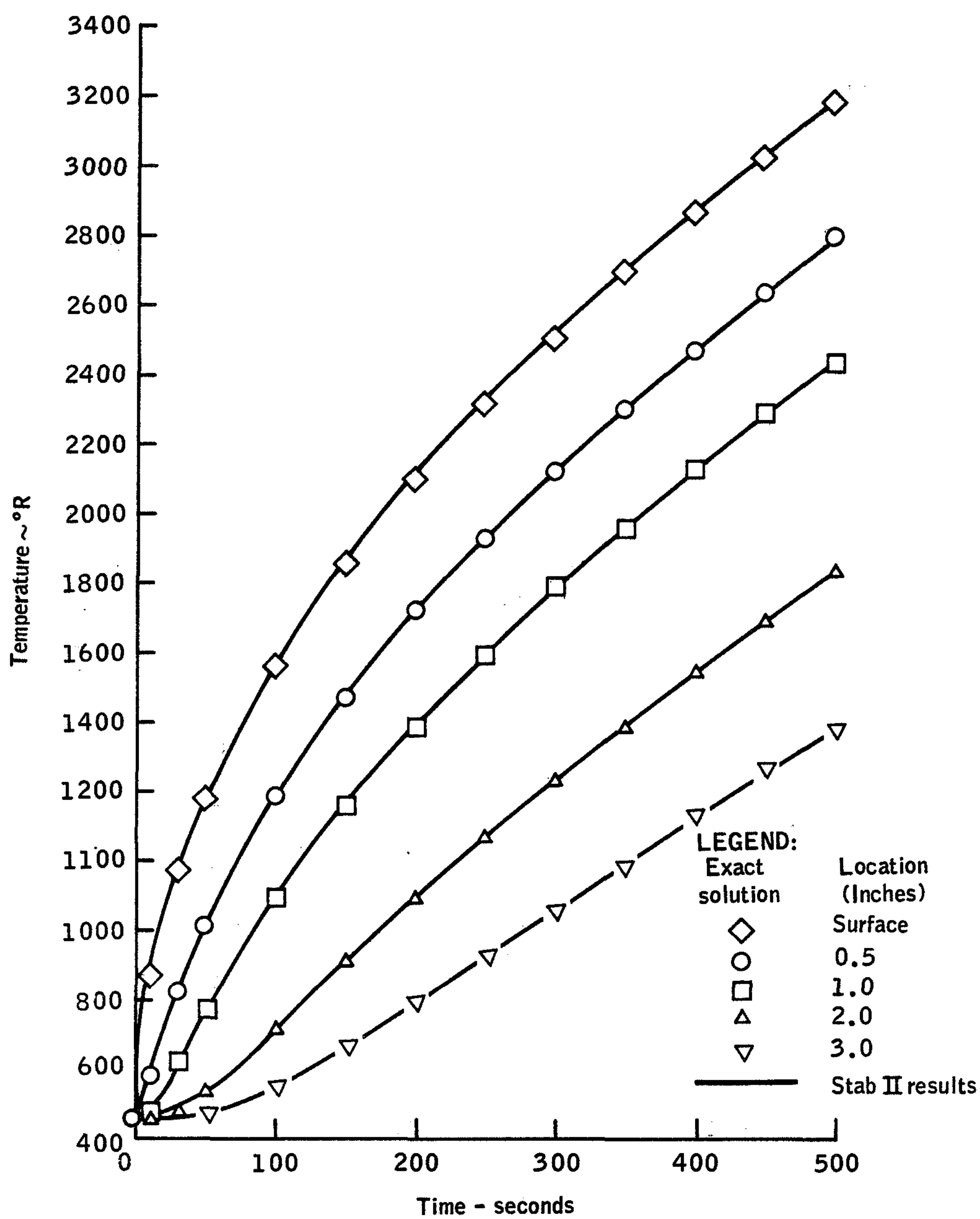


Figure 5.- Comparison of temperature histories for nonablating steel slab (pure conduction).

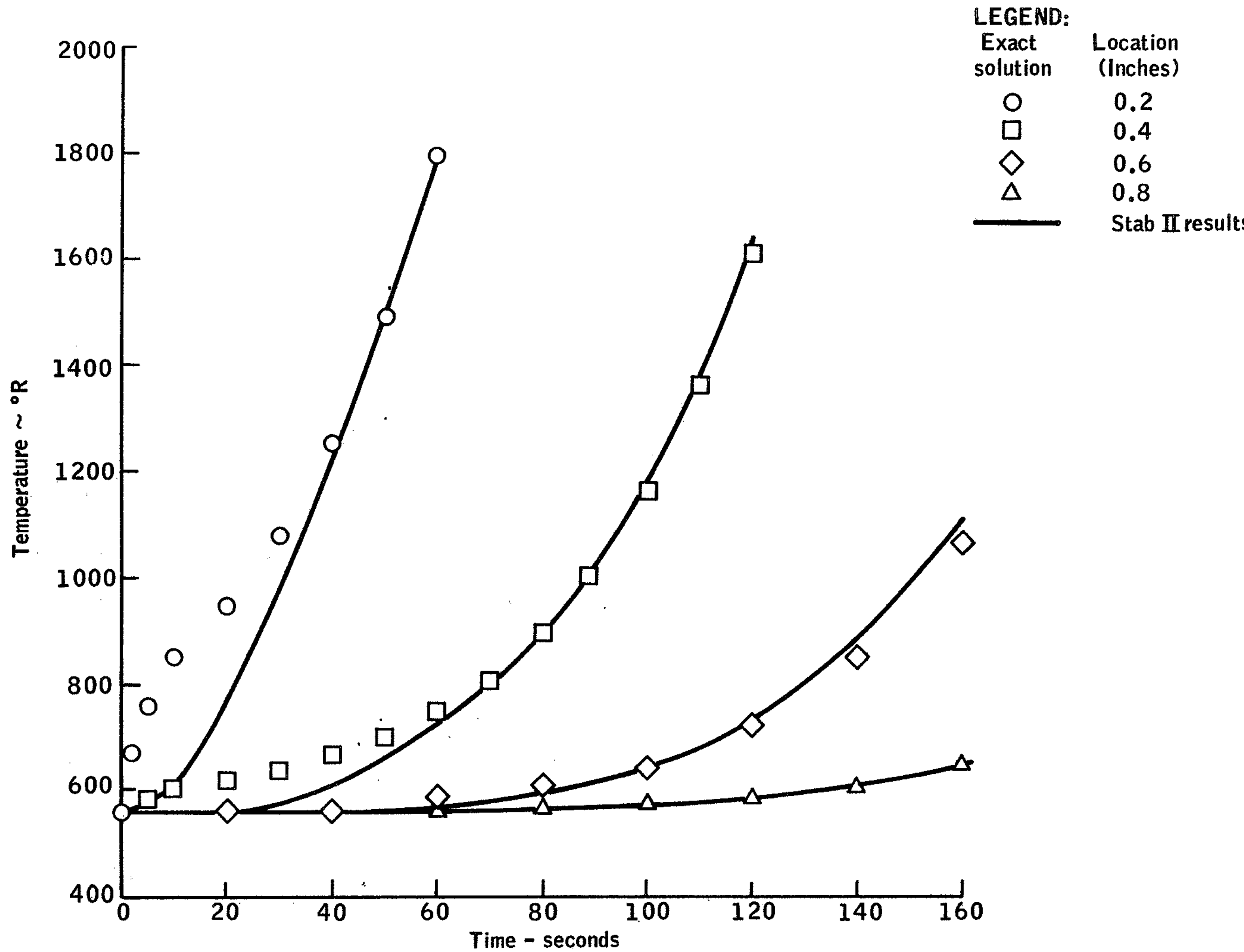


Figure 6.- Comparison of temperature histories for moving boundary model.

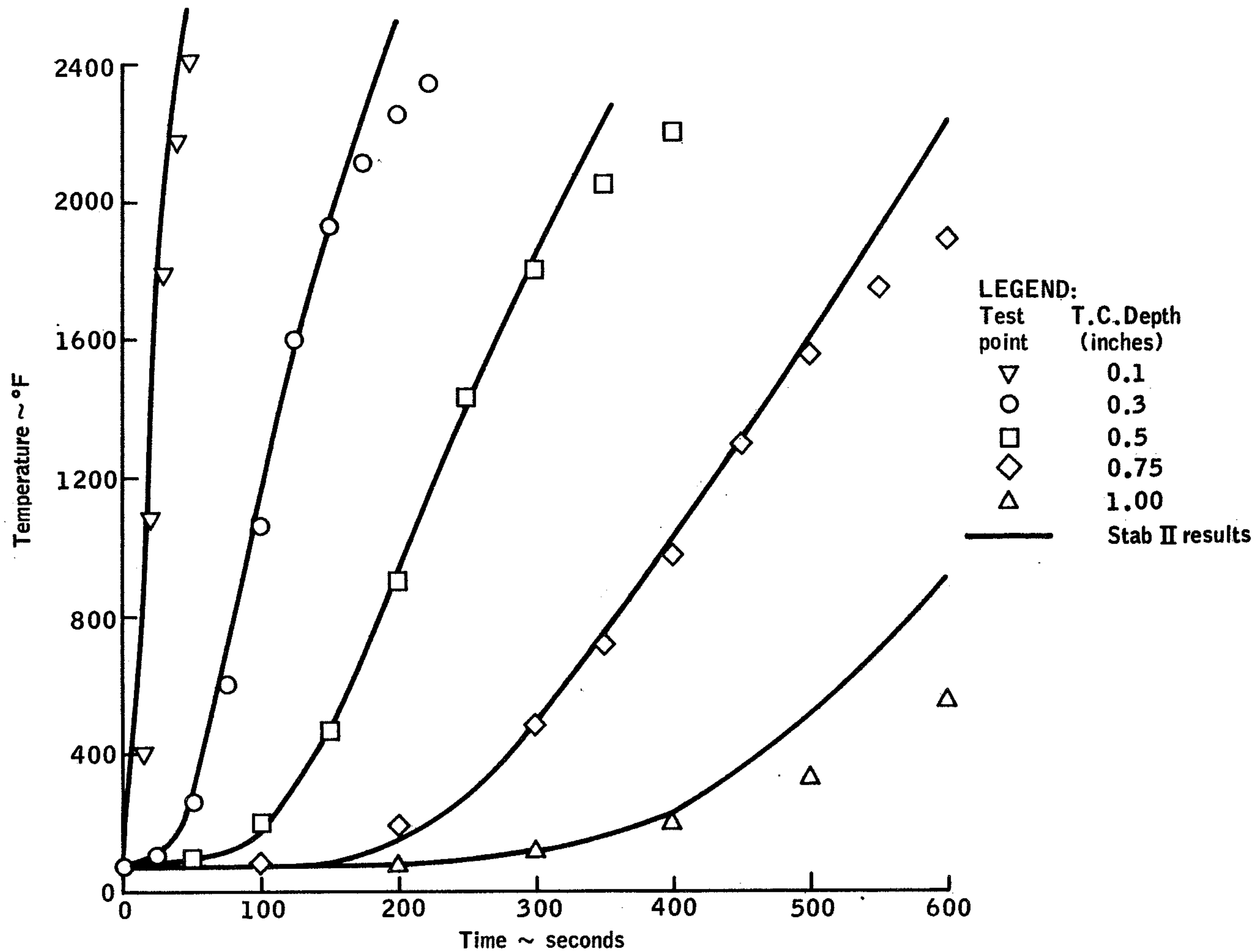


Figure 7.- Comparison of temperature histories for typical charring ablator.

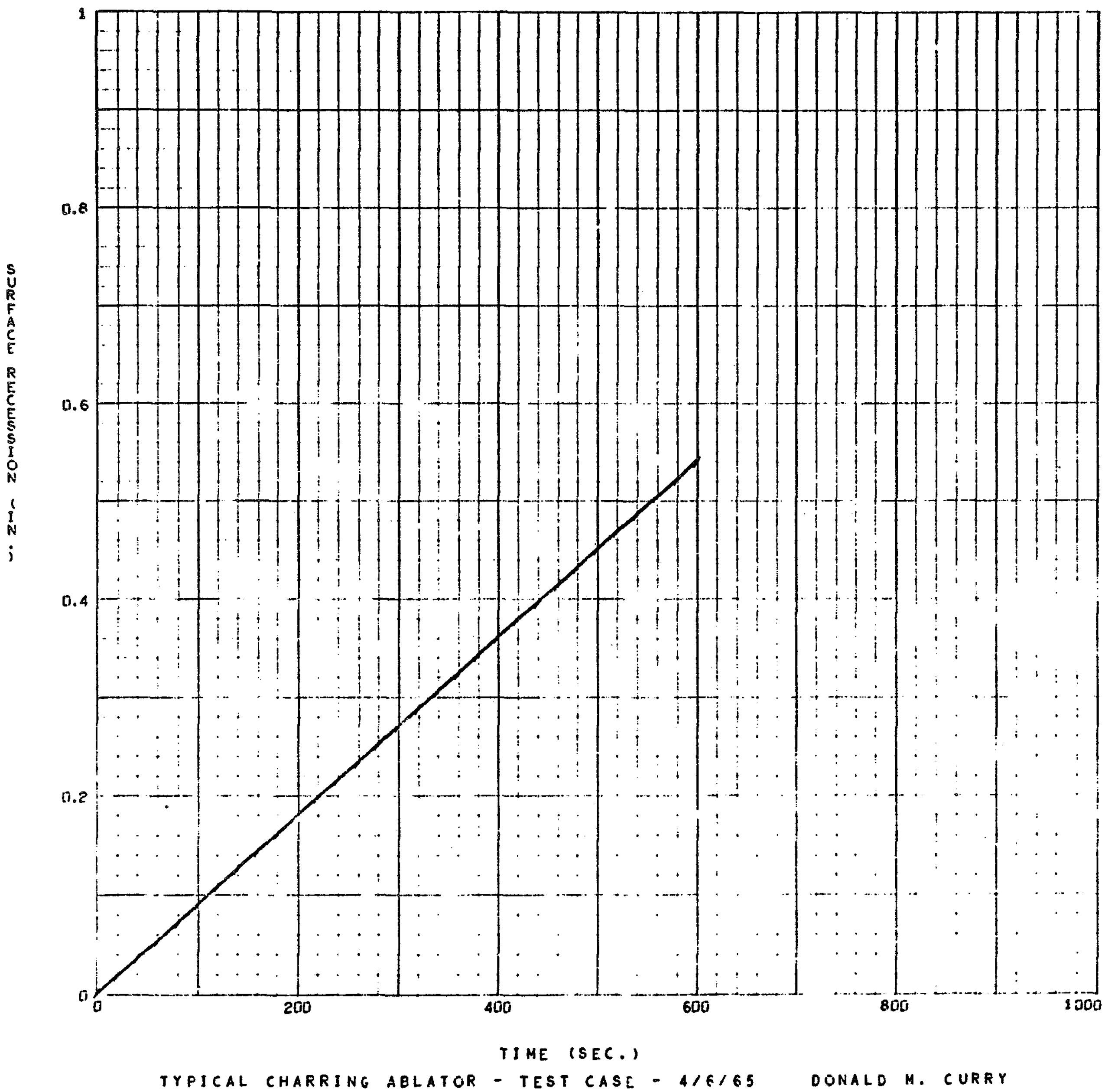


Figure 8. - Plot program surface recession curve from typical charring ablator test case.

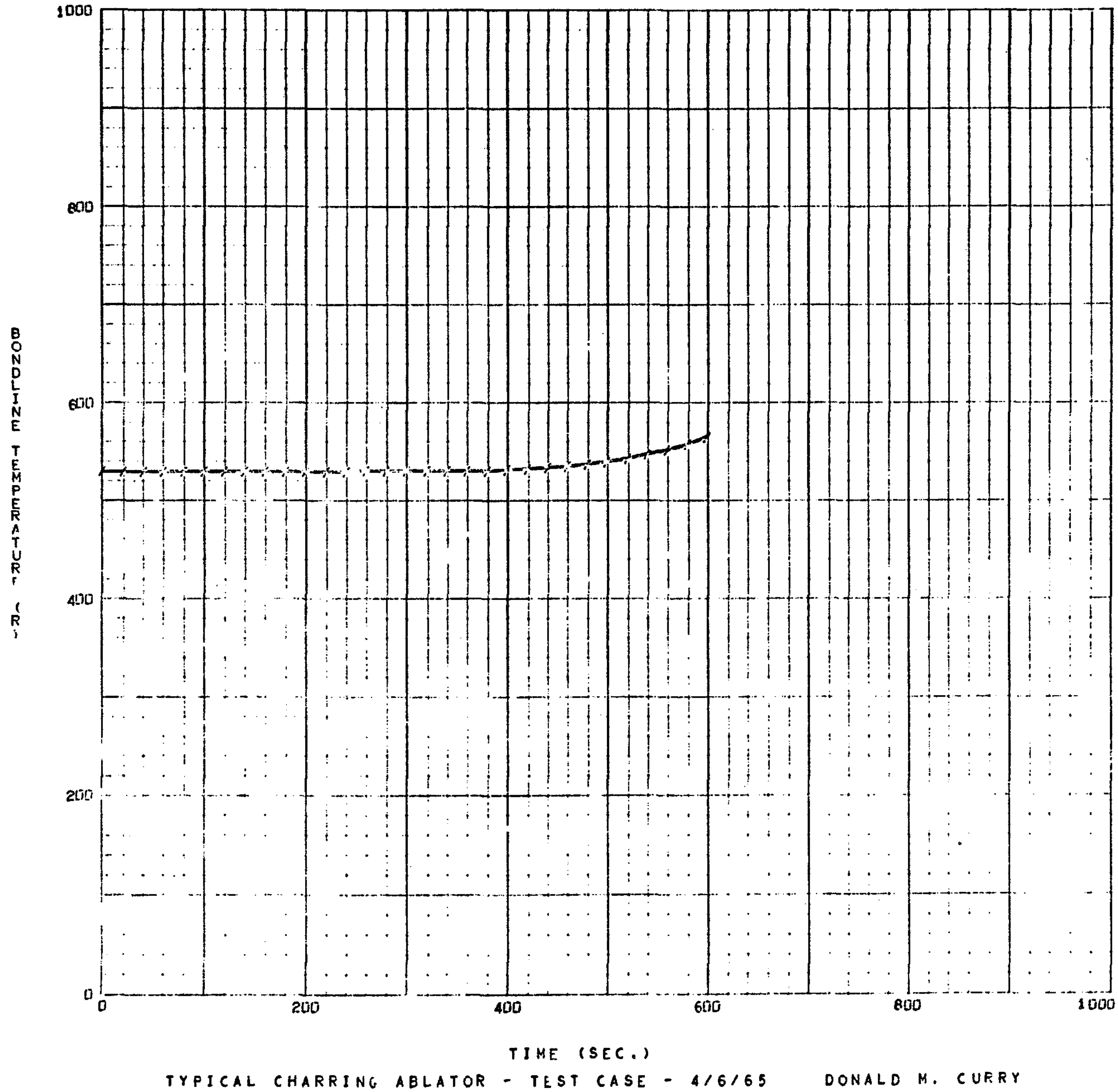


Figure 9. - Plot program bondline temperature curve from typical charring ablator test case.

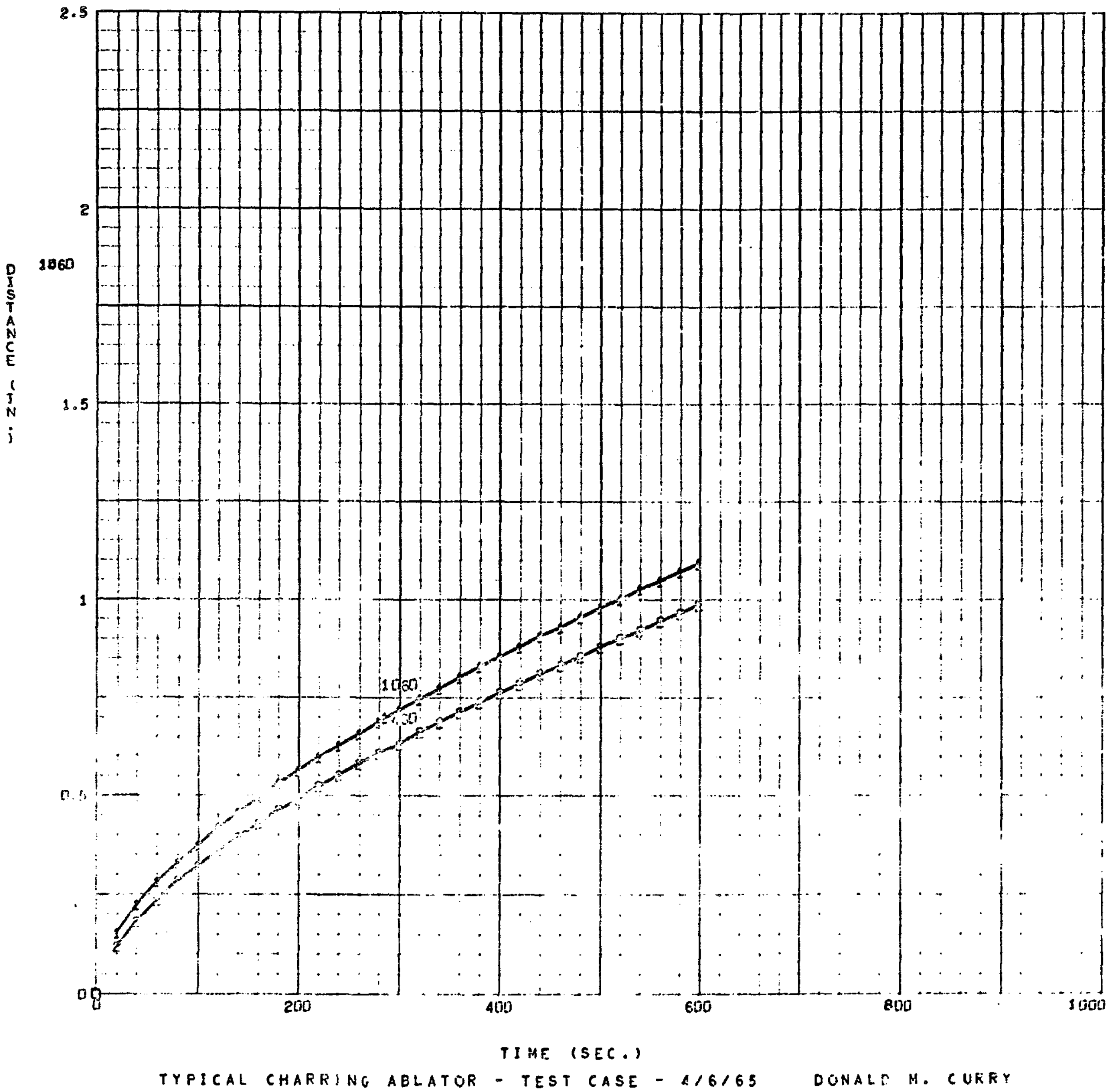


Figure 10. - Plot program isotherm curves from typical charring ablator test case.